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THE EFFECT OF COMPRESSIVE LOADING ON THE FATIGUE LIFETIME OF GRAPHITE/EPOXY LAMINATES

LOCKHEED-CALIFORNIA COMPANY
RYE CANYON RESEARCH LABORATORY
BURBANK, CALIFORNIA, 91520

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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J. M. WHITNEY, Project Engineer
Mechanics & Surface Interactions Br.
Nonmetallic Materials Division

S. W. TSAI, Chief
Mechanics & Surface Interactions Br.
Nonmetallic Materials Division

FOR THE COMMANDER

J. M. KELBLE, Chief
Nonmetallic Materials Division

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The main objective of this research investigation was the effect of compressive loading on the fatigue response of graphite epoxy laminates as influenced by a circular hole and an aggressive environment. The investigation was undertaken in order to further characterize the behavior of graphite/epoxy laminates under fatigue loading. The primary emphasis of the program was on the accumulation of a statistically significant data base. Unnotched coupon properties of a quasi-isotropic and a 67% 0° fiber laminate were investigated in a 82.2°C (180°F), 90% R.H. environment after prior conditioning in that (continued)

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environment. The interactional effects of absorbed moisture and fatigue loading on the fatigue lifetime of coupons containing a circular hole was investigated at room temperature and at 82.2°C (180°F), 90% R.H. using the quasi-isotropic laminate. The test program consisted of static tension and compression tests; tension-tension and tension-compression fatigue tests; and static tension and compression residual strength tests of coupons prior tested either under tension-tension or tension-compression fatigue loading.

Absorbed moisture was found to significantly affect static, fatigue, and residual strength response of the laminates. Higher levels of absorbed moisture resulted in reduction of mechanical properties. The scatter in fatigue properties was found to be significantly reduced if variations due to absorbed moisture and defects internal to the material were taken into account. Suggestions for a general engineering design procedure for graphite/epoxy laminates are discussed.

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SECTION I

INTRODUCTION

The main objective of this research investigation was the effect of compres-
sive loading on the fatigue response of graphite/epoxy laminates as influenced
by a circular hole and an aggressive environment. The investigation was under-
taken in order to characterize the behavior of graphite/epoxy laminates under
fatigue loading. This characterization provides supportive information for
verifying that such materials can meet current Air Force design requirements
of damage tolerance. The primary emphasis of the program was on the accumu-
lation of a statistically significant data base.

A previous research study [1] showed that graphite/epoxy composites under
constant amplitude loading exhibit stress-life fatigue behavior similar to
that observed for metals. The fatigue data has large scatter, but practical
fatigue limits do exist (stress levels below which no fatigue failures are
encountered before 10^6 cycles). Compression load excursions do significantly
reduce fatigue life, but, within practical limits, they could be accounted
for by stress range rather than the absolute value of the maximum load. Since
the entire previous study was conducted in ambient air conditions (21 ± 2°C,
40 ± 10% R.H.), the affect of absorbed moisture and temperature on tension-
tension and tension-compression fatigue remained unknown.

Absorbed moisture reduces the structurally useful temerature range of epoxy
resins. Long term temperature exposure below 93.3°C (200°F) normally has
little effect on mechanical behavior of presently used graphite/epoxy com-
posites. However, if a significant amount of absorbed moisture occurs, static
strength mechanical properties can degrade [2]. This problem can be particu-
larly significant under compressive loading [2] because the matrix provides
lateral support for the fibers. Therefore, any softening of the matrix due

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to absorbed moisture is of structural concern. The effect of absorbed mois-
ture and associated matrix softening on fatigue properties, especially under
compressive loading, has not previously been reported.

Also of interest in this study was the interactional effect of absorbed
moisture and fatigue loading on the lifetime of graphite/epoxy laminates
containing circular holes. This interactional problem arises because of
the frequency of holes in present composite structure. Therefore, notched
coupons were included in this study to give some indication as to their
sensitivity to either absorbed moisture or fatigue loading, or both.

The principal features of the sequential investigation are shown in Figure 1.
Phase 1 consisted of fabrication of unnotched and notched specimens with as
nearly consistent properties as practical. In Phase 2, initial static strength
distributions were determined along with stress-strain curves where appro-
priate. Following this, Phase 3 established the general stress-life (S-N)
behavior of the material for both tension-tension and tension-compression
fatigue. The preliminary screening tests at several stress levels were used
to determine the general shape of the S-N curves and aid in selection of
subsequent stress levels at which statistically based fatigue life distri-
butions were to be determined. Residual strength fatigue tests conducted
to two different fatigue lives and static residual strength distributions
were determined in Phase 4. One stress level for each S-N curve was selected.
Phases 1 to 4 were conducted using a quasi-isotropic laminate (both notched
and unnotched) and an unnotched 67% 0° fiber laminate. Experimental results
were analyzed in Task II. Data analysis included estimation of Weibull para-
meters. Investigation of analytical models was primarily concerned with
evaluation of the "wear-out" type of model where the specific rate-decay
equation and limits of integration are selected based on data trends and
physical evidence of mechanisms.

TASK I

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┌─────────────────────────────┐
│          PHASE 1            │
│    SPECIMEN FABRICATION     │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│          PHASE 2            │
│       STATIC TESTING        │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│          PHASE 3            │
│      FATIGUE TESTING        │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│          PHASE 4            │
│  RESIDUAL STRENGTH TESTING  │
└─────────────────────────────┘
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TASK II

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┌─────────────────────────────┐
│                             │
│  DATA ANALYSIS AND FATIGUE  │
│     MODEL DEVELOPMENT        │
│                             │
└─────────────────────────────┘
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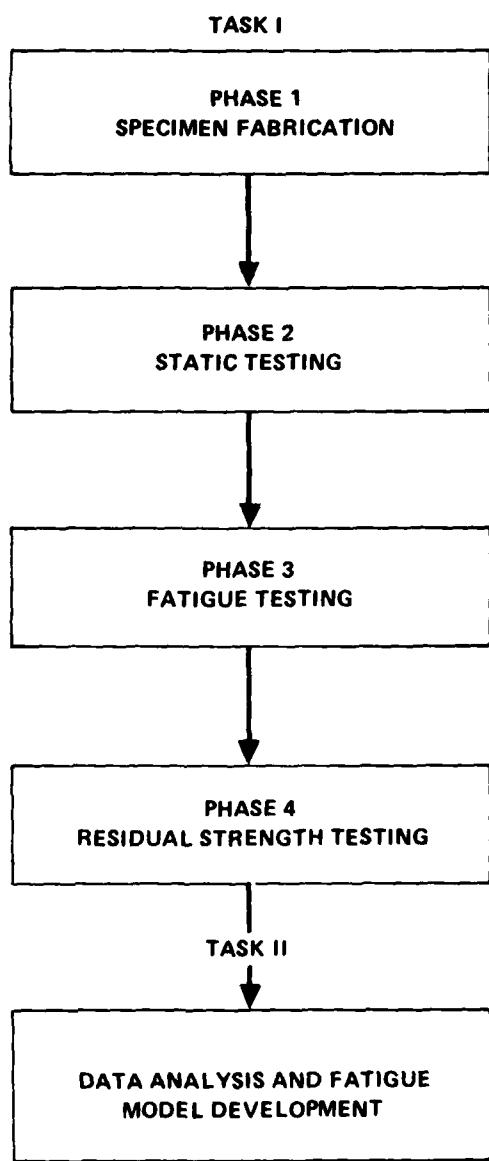
Figure 1.   Program Outline

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SECTION II

PROGRAM OVERVIEW

This section presents a discussion of the rationale for material and laminate selection, outlines the program test matrix, and describes the test procedures.

2.1 MATERIAL SELECTION

The selected fiber/resin system was Fiberite system HY-E-1034C (Thronel T300 Fiber/Fiberite 934 Resin). This is the same fiber/resin system as used previously to obtain the room temperature, laboratory air data of unnotched coupons [1] and was selected to maintain continuity of selection. The basis of the original selection was as follows.

The number of graphite material systems which have emerged in the recent history of advanced composites and which were viable for acceptance in this program were numerous. However, changes in system designation have been more a consequence of changes in the epoxy resin system than in the graphite fiber. An in-depth review of available graphite/epoxy systems led to the conclusion that the basic material selected for use on this program should consist of a low-cost, high strength graphite fiber such as the Hercules AS type or the Union Carbide Thornel 300. The matrix material was chosen as a 177°C (350°F) cure epoxy to be selected from one of the following: Hercules 3501, Narmco 5208, or Fiberite 934. The fiber/resin combinations considered for this program were Hercules' Magnamite (AS/3501), Narmco's Rigidite (T300/5208), Fiberite's HY-E-1034C (T300/934) and HY-E-1334C (AS/934). Fiber/resin systems employing the AS fiber or 3501 resin were eliminated on the basis of limited data [3] which indicated that they had excessively wide property variations at the time of the inception of this program. The Narmco Rigidite (T300/5208) system was eliminated because this system has extreme producibility problems under normal manufacturing conditions.

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2.2 LAMINATE SELECTION

The two laminates chosen for the investigation were the same as those previously selected [1]. The two laminates used were a quasi-isotropic, 25% $0°$ fiber laminate and a 67% $0°$ fiber laminate. The selected laminates were:

$$\text{Laminate 1:} \quad (0/45/90/-45_2/90/45/0)_S$$

$$\text{Laminate 2:} \quad (0/45/0_2/-45/0_2/45/0_2/-45/0)_S$$

The first laminate was chosen because of possible wide application and because the fatigue damage was expected to be dominated by matrix delamination between plies. The second laminate was chosen because the fatigue damage was expected to be dominated by the delamination of fiber bundles without delamination between plies occurring to any significant extent until late in the fatigue life.

Laminates for aircraft structures are typically selected for convenience from the $0_i/\pm45_j/90_k$ orientation family. The $0°$ direction is generally oriented parallel to the principal axial loading direction; $\pm 45°$ plies provide shear strength and stiffness or buckling resistance; and $90°$ plies provide additional strength in the transverse direction when required. The judicious addition of $90°$ plies to $0_i \pm 45_j$ laminates reduces the Poisson's ratio, can be used to mitigate some of the free edge stresses, and can result in strength and stiffness benefits depending on the loading direction.

However, the $90°$ plies may crack at a small fraction of the ultimate tensile strength of the laminate complicating the fatigue phenomenon.

The selection of stacking sequences for the laminates considered the following:

(a) Mirror symmetry about the mid-plane was maintained to minimize warping or curling during manufacture or under load.

(b) Stacking order was considered because of the severe effects on the flexural stiffness and, consequently, the buckling behavior of the laminate. A wide column has a maximum buckling surface when the $0°$ plies are at or near the outer surface.

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(c) For optimum load transfer the ply adjacent to a bonded tab joint was oriented with the fibers parallel to the direction of loading.

(d) Adjacent plies were oriented (when possible) to minimize the angle between adjacent plies. Studies [4] have shown micro-cracking can occur from curing stresses if adjacent plies are oriented at greater than 60°. The same rule applies to the transfer of interlaminar shear stresses [5]. While not normally affecting static strength, this can affect fatigue strength.

(e) The stacking sequence can cause interlaminar normal stresses to occur at the free edge of the laminate. Interlaminar tension stresses can cause delamination under both static and cyclic loading. The sign (tension or compression) of the normal stress depends both on the sign of the laminate in-plane loading and the stacking sequence. A given ply set can be stacked in such a way that maximum or minimum tension or compression, σ_z, can be obtained.

Obviously, simultaneous satisfaction of all the above criteria for a given structural element required compromises. Items (c) and (d) frequently conflicted with item (b), and the development of a stacking sequence that minimized interlaminar normal and shear stresses (item e) also conflicted with (b) and (c). Stacking the laminate so that the normal stresses are compressive is generally believed to increase the fatigue strength over that of a laminate with tensile normal stresses. However, cyclically applied loading with reversing direction results in reversal of the sign of the normal stress. Consequently, for the fatigue coupons of this program, which were subjected to both tension compression loading, laminae were stacked to minimize normal stresses over the entire range of loading and thus minimize their effects on fatigue life.

2.3   FABRICATION AND QUALITY ASSURANCE PROCEDURES

Essentially, fabrication and quality assurance procedures followed those used previously in Contract F33615-75-C-5118 [1]. The procedures are outlined in this section. Appendix A contains the detailed fabrication procedure used in this study. Table 1 outlines the steps taken to assure test panel quality and uniformity.

TABLE 1

QUALITY ASSURANCE TESTING OUTLINE

Material Form	Test
Prepreg (receiving inspection)	- Visual examination (fiber uniformity, fiber alignment) - Volatiles content - Uncured resin content - Control of shelf life
Layup (prior to cure)	- Visual examination of excess section for proper orientation of each ply
Curing	- Automated autoclave programming for control of cure parameters - Permanent records of cure temperature and pressure maintained for each autoclave run
Cured Laminates	- Visual examination (resin starvation, fiber wash-out, pinholes, etc.) - Thickness per ply - Cured resin content - Density - Void content (calculated) - Examination of cross-section under magnification - Nondestructive inspection of each test laminate by ultrasonic "C" scan

Prepreg Quality Assurance - A single batch of 305-mm (12-in.) wide prepreg
was used for all test laminates thus preventing the possibility of the data
being affected by batch-to-batch variations. The assumption was made (and was
supported by previously obtained results [1]) that after coupons have been
manufactured, no significant change in their properties would occur during
room temperature, 40 ± 10% R.H. shelf storage. Although this assumption
was not expected to be perfectly true over the 18 month testing period of
this contract, the variation in properties due to long term storage was ex-
pected to be less than that due to batch-to-batch variations. This assump-
tion was supported by the data results obtained.

Resin content, volatiles content, and flow of the prepreg were inspected for
conformance to specified tolerances upon receipt. Prepreg material was also
inspected for flaws such as fiber misalignment, breakage, gaps, excess resin,
and starved areas, and any portions of the batch containing these flaws re-
jected.

Storage of Prepreg Materials - All prepreg materials were stored in sealed
moisture proof bags in refrigerators at -17.8°C(0°F) to assure adequate
shelf-life. Materials which exceeded specified storage periods were not
used.

Layup of Laminates - Before layup, all materials, when removed from refriger-
ators, were allowed to come to room temperature before unsealing bags to
prevent water condensation on prepreg surfaces. Layup of laminates was per-
formed in a semi-clean room with temperature controlled to 21 ± 2°C (70 ± 5°F).
This reduced contamination with dust or foreign matter. Controlled temperature
assured proper tack and drape of prepregs and prevented water condensation
problems. Fiber orientation in a layup was accomplished by use of suitable
templates to meet the required angle tolerances of ± 1/2°.

Curing of Laminates - Test laminates were fabricated in an autoclave using
vacuum pressure augmented by autoclave pressure. The autoclave used incorporate

automatic programming instrumentation to control dwell time and heating rates. In the autoclave, pressure was not dependent upon tool or platen quality. These factors minimized the variation between separate cure operations. Test laminate fabrication required more than one autoclave cycle, but close controls reduced the possibility of significant test panel variations.

Bleeding was accomplished by use of a perforated, releasable membrane placed in contact with the laminates and backed with an absorbent material. This permitted escape of air and volatiles as well as bleeding of resin to reduce resin content of the laminates to specified levels. Pressure bags of suitable heat resistant plastic film were sealed in place over the layup.

Prior to cure, an excess section of the layup was examined to ensure proper filament orientation in each ply. During the cure cycle, a complete permanent record was maintained of temperature, vacuum pressure, and autoclave pressure. This record included heat-up rates and times of pressure application and release.

Test laminates were visually examined for defects such as resin starvation, fiber wash-out, pinholes, and voids. Thickness per ply, cured resin content, and density were determined. Weight percent fiber and resin were measured on each panel by replicate determinations using the acid digestion method. Density was measured by the water displacement method. From the known fiber and resin densities, fiber volume fraction and void volume fraction were calculated. All panels were fabricated such that a 25.4-mm (1.0-in.) wide edge could be trimmed off on all sides.

Each test laminate panel was nondestructively inspected by ultrasonic C scan procedure for voids, delaminations and other defects. NDI standard references were incorporated into each panel which consisted of three Teflon 0.05 mm (0.002-in.) thick film pads 3.2 to 12.7-mm (1/8 to 1/2-in.) diameter placed in the upper right hand corner. The references in each panel were compared to standard panels fabricated identical to the laminate 1 and 2 panels used in the test program except that 0.05-mm (0.002-in.) thick Teflon film pads of

ALL DIMENSIONS IN MILLIMETERS

SPECIMENS TO BE FLAT OVER THE ENTIRE 267-MM (10.5-IN.) LENGTH WITHIN 0.25-MM (0.01-IN.)

TAB EDGES TO BE PARALLEL TO SIDES OF SPECIMEN WITHIN 0.025-MM (0.001-IN.) OVERHANG NOT TO EXCEED 3.8-MM (0.003-IN.)

THE TAB AND SPECIMEN BONDING SURFACES TO BE THOROUGHLY SOLVENT CLEANED USING METHYL-ETHYL-KETONE PRIOR TO BONDING. A 350°F CURING ADHESIVE IS TO BE USED AND MUST COVER ENTIRE SURFACE UNIFORMLY.

SPECIMENS TO BE CUT DRY. MACHINED SURFACES TO BE RMS 50 OR BETTER. NO EDGE DAMAGE OR FIBER SEPARATION SHOULD BE VISIBLE UNDER 10X MAGNIFICATION.

MEASURE SPECIMEN WIDTH 4 PLACES. WIDTH MUST NOT VARY BY MORE THAN 0.102-MM (0.004-IN.)

SPECIMEN WIDTH TO BE 22.225±0.127-MM (0.875±0.005-IN.)

MISMATCH OF TABS FROM SIDE TO SIDE NOT TO EXCEED 0.25-MM (0.01-IN.)

TABS TO BE CUT FROM AN 8 PLY LAMINATE FABRICATED FROM PREPREG OF 1581 GLASS FABRIC IN A 350°F CURING EPOXY.

SPECIMEN THICKNESS TO BE WITHIN ±0.08-MM (±0.003-IN.) OF THE AVERAGE OF 8 THICKNESS MEASUREMENTS.

Figure 2. Specimen Configuration, Un-notched

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ALL DIMENSIONS IN MILLIMETERS

9 SPECIMENS TO BE FLAT OVER THE ENTIRE 267-MM (10.5-IN.) LENGTH WITHIN 0.25-MM (0.01-IN.)

8 TAB EDGES TO BE PARALLEL TO SIDES OF SPECIMEN WITHIN 0.025-MM (0.001-IN.) OVERHANG NOT TO EXCEED 3.8-MM (0.003-IN.)

7 THE TAB AND SPECIMEN BONDING SURFACES TO BE THOROUGHLY SOLVENT CLEANED USING METHYL-ETHYL-KETONE PRIOR TO BONDING. A 350°F CURING ADHESIVE IS TO BE USED AND MUST COVER ENTIRE SURFACE UNIFORMLY.

6 SPECIMENS TO BE CUT DRY. MACHINED SURFACES TO BE RMS 50 OR BETTER. NO EDGE DAMAGE OR FIBER SEPARATION SHOULD BE VISIBLE UNDER 10X MAGNIFICATION.

5 MEASURE SPECIMEN WIDTH 4 PLACES. WIDTH MUST NOT VARY BY MORE THAN 0.102-MM (0.004-IN.)

4 SPECIMEN WIDTH TO BE 22.225±0.127-MM (0.875±0.005-IN.)

3 MISMATCH OF TABS FROM SIDE TO SIDE NOT TO EXCEED 0.25-MM (0.01-IN.)

2 TABS TO BE CUT FROM AN 8 PLY LAMINATE FABRICATED FROM PREPREG OF 1581 GLASS FABRIC IN A 350°F CURING EPOXY.

1 SPECIMEN THICKNESS TO BE WITHIN ±0.08-MM (±0.003-IN.) OF THE AVERAGE OF 8 THICKNESS MEASUREMENTS.

Figure 3. Specimen Configuration, Notched

3.2 to 12.7-mm 1/8 to 1/2 in.) diameter were placed at eight locations in the upper and lower halves of the standard panel. The appropriate reference panel was used as a standard for the NDI scan inspection of the laminate 1 and laminate 2 test panels.

The panel and coupon fabrication procedure used in this program is attached to this report as Appendix A. For laminate 1, eleven panels were fabricated of approximate dimensions, 914 x 1219-mm (36 x 48-in.) while for laminate 2 five panels were fabricated of the same approximate dimensions as for laminate 1 panels.

Specimen Design - Figure 2 shows the specimen design for the un-notched coupon. This design has the same overall dimensions, gage length and width as that used previously in Contract F33615-75-C-5118 [1]. Figure 3 shows the notched coupon design. This geometry for the notched coupon was selected in order to make a direct comparison between un-notched and notched data. A research study [6] conducted to systematically investigate the effect of geometry on the fatigue properties of graphite/epoxy laminate strongly indicated that characteristic fatigue life is dependent on geometry. Details for the machining of these coupons are given in Appendix A.

After fabrication and prior to testing, the thickness of all coupons was measured in eight places and the width in four places (see Figure 4 for these locations). The width of any one coupon varied at most ± 0.0127-mm (± 0.0005-in., ± 0.06%) within the gage length. The width of all coupons varied by less than ± 0.10-mm (± 0.004-in.) within the gage lengths. The area of any one coupon was found to vary by less than ± 1.5% and that of all coupons by less than ± 4% within the gage length.
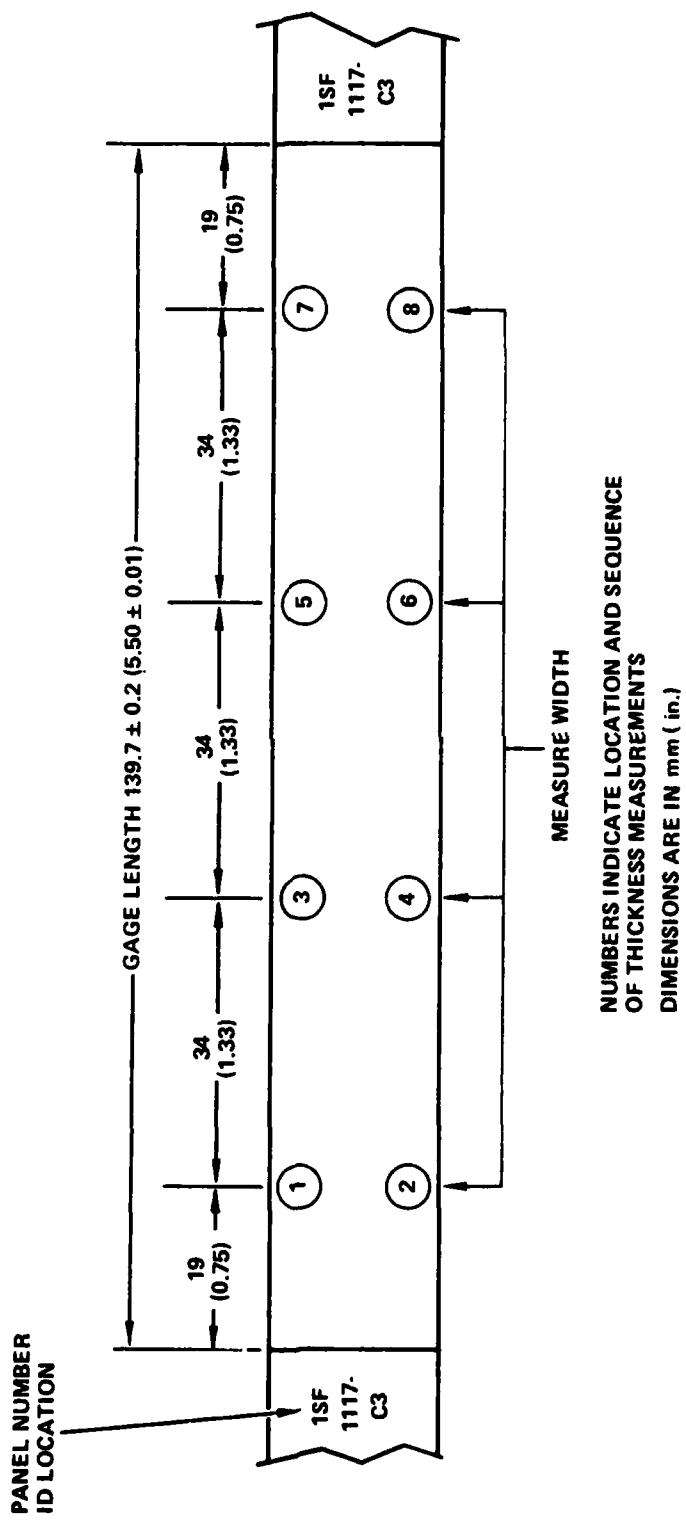
Figure 4. Location of Thickness and Width Measurements

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All coupons were identified by the following system:

Panel No.   Material Batch Code
Within Autoclave
Run (1 or 2)

<u>1 SF 1117</u> - <u>B 17</u>

Autoclave   Coupon No.
Run Series No.   Laminate Panel No.   Sub-Panel No.
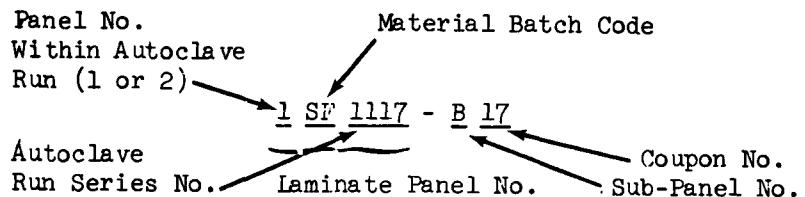
Autoclave and panel numbers are consecutive at Lockheed and are an internal reference number unique to each panel. The test panels were cut into four sub-panels, and numbered from the top as A, B, C, and D. This system of coupon identification allowed for traceability of each coupon to previous panel location and of each panel to fabrication history.

A test panel of older material was laid up for evaluating tab adhesives so that one could be selected capable of being used under the most extreme testing condition to be encountered in the test program, namely tension-compression fatigue at 82.2°C (180°F) and 95% R.H. Adhesive systems selected for study were American Cyanimide FM73, FM300, FM400, and HT 424. The FM73 is a 121°C (250°F) cure system while the other three adhesives are 177°C (350°F) systems. The FM73 and FM300 adhesive quickly failed adhesively under room temperature tension-compression fatigue conditions while the HT424 failed at high temperature and humidity. The FM400 system appeared to maintain tab integrity under all testing conditions, therefore this material was selected for use in this program.

2.4   TEST PROGRAM

The test program is presented in Table 2. Tests were divided into two main groups: notched and un-notched. Within each group three types of tests were conducted.

    o Static tension and compression

    o Tension-tension and tension-compression fatigue

    o Static tension and compression residual strength tests after tension-tension or tension-compression fatigue

All un-notched tests were conducted in a high temperature, high humidity environment except for a few tests at room temperature to allow for comparison

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TABLE 2.
TEST MATRIX

TEST CATEGORY	TEST TYPE	LAMI-NATE	TESTING ENVIRONMENT	NUMBER OF STRESS LEVELS	NUMBER OF COUPON REPLICATIONS	TOTAL NO. OF TEST CONDITIONS
Material Characterization (Un-notched Coupons)	Static Tension	1,2	D[a]	T[c]	5/panel (16 panels)	80
Effect of a Circular Hole (Notched Coupon)	Static	1	D,W[b]	2(T,C)[c]	20	80
	Fatigue Screen T-T	1	D,W	8	3	48
	T-C	1	D,W	8	3	48
	Scatter T-T	1	D,W	3	20	120[e]
	T-C					
	Residual Strength T-T	1	D,W	2(T,C) x 2[d]	20	160
	T-C	1	D,W	2(T,C) x 2[d]	20	160
Effect of Environment on Un-notched laminates (Un-notched Coupons)	Static	1,2	D,W	2(T,C)	20	160[f]
	Fatigue Screen T-T	1,2	D,W	8	3	96
	T-C	1,2	D,W	8	3	96
	Scatter T-T	1,2	W	3	20	120[e]
	T-C	1,2	W	3	20	120[e]
	Residual Strength T-T	1,2	W	2(T,C) x 2[d]	20	160[g]
	T-C	1,2	W	2(T,C) x 2[d]	20	160[g]

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TABLE 2. (Continued)
TEST MATRIX

TEST CATEGORY	TEST TYPE	LAMI- NATE	TESTING ENVIRONMENT	NUMBER OF STRESS LEVELS	NUMBER OF COUPON REPLICATIONS	TOTAL NO. OF TEST CONDITIONS
Static Scatter	Static	2	D	T	100	100[h]
Fatigue Threshold	Fatigue	1	D	2(T-T,T-C)	20	40[i]

a - D = 72° ± 2°F, 40 ± 10% R.H., laboratory air environment

b - W = 180°F, 90% R.H., laboratory air environment

c - T = Tension
    C = Compression

d - Residual strength at two different lives was determined

e - 18 of these coupons were tested in the fatigue screening program

f - Note that 40 of the tension tests were tested in material characterization

g - For laminate 2, some of these coupons were obtained from the fatigue scatter study

h - These tests include 20 coupons previously tested under Contract F33615-75-C-5118 [1]; the remaining 80 coupons came from panels fabricated for the same contract

i - These 40 coupons came from panels fabricated under Contract F33615-75-C-5118 [1]

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to data previously generated in Contract F33615-73-C-5118 [1]. These un-notched tests involved equal numbers of laminate 1 and laminate 2 coupons. All notched coupons were of the laminate 1 layup and involved equal numbers of coupons tested at room temperature and at high humidity, high temperature.

Since a primary objective of this study was to establish a firm statistical basis for all test results, a random sampling procedure was employed for coupon selection. Essentially, this program chose the test condition for each sample in a double-blind random manner. The number of randomly selected coupons to be tested per condition was chosen to adequately insure a large enough data set for obtaining statistically meaningful and reliable distributions of fatigue life and static residual strength. Based on previous results [1], at least 15 coupons were selected to be tested at each test condition.

After fabrication, all coupons were kept in a chamber maintained at 22 ± 1°C (72° ± 2°F) and 40 ± 10% relative humidity in a laboratory air environment. This environmental condition was called the standard, room temperature, dry condition. Weight gain coupons were used to monitor moisture pickup in this environment. They were periodically measured to determine their percent weight gain. Coupons tested at high temperature were removed from the room temperature conditioning environment and conditioned at 82.2 ± 1°C (180° ± 2°F) at 90 ± 3% R.H. until they reached equilibrium. Coupons were conditioned in batches so that no coupon would remain in the high temperature environment for an excessive time prior to testing. Weight gain coupons accompanied each batch and were used to monitor moisture pickup. Selected weight gain coupons were dried out after stabilization was reached and weight loss measured to establish the actual moisture content. Since all high temperature tests were conducted in the same environment used to condition the coupons, problems of moisture absorption stabilization were reduced to a minimum.

The static tension and compression stress-strain curves, ultimate strength, and apparent modulus of elasticity (where appropriate) were determined for each of the two laminate orientations. For constant amplitude fatigue

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(at 10 Hz), approximate tension-tension and tension-compression S-N curves
were obtained for both laminates using three specimens at each of several
stress levels. Coupons were cycled to failure or to 10^6 cycles, defined as
run-out, although many coupons were cycled longer and a few tests were in-
terrupted at 5×10^5 cycles. Based on the results of the approximate S-N
curves, stress levels were chosen from each S-N curve for study of data
scatter under tension-tension and tension-compression fatigue testing. At
each of the stress levels, at least 15 specimens were cycled.

The tension and compression residual strength of specimens tested in tension-
tension and tension-compression fatigue were determined. For each of the
stress-life curves, one fatigue stress level was selected for determining
residual strength. At each stress level, coupons were fatigue cycled to
one of two different propability of survival levels. For laminate 1, the
number of cycles was selected to be approximately equivalent to the life
where 90% or 50% of the coupons could be expected to have survived as esti-
mated from the prior data obtained to develop the fatigue life behavior. For
laminate 2, the number of cycles was chosen as 10^6 or 2.5×10^5 cycles of
fatigue loading. For each group of specimens, half were static tested in
tension and the other half in compression. Stress-strain curves, ultimate
strength, and apparent modulus of elasticity (where appropriate) were recorded.

Additional tests were conducted using coupons from a previous Air Force
contract [1]. These investigations studied the effect of strain rate on
static strength and the existence of a fatigue threshold.

2.5   TESTING PROCEDURES

For both static tension and compression tests, load and deflection were con-
tinuously read out on an X-Y recorder so that stress-strain curves could be
constructed. Ultimate strength, strain to failure, and the apparent modulus
of elasticity were calculated. Stress was calculated using the average area
based on four locations equally spaced within the gage length.

An enclosure (metal or acrylic) surrounded the static test equipment for elevated temperature testing, Figure 5. The internal space is supplied with heated air. This arrangement provided specimen temperatures which were uniform throughout the gage length and controlled to $\pm$ 1°C ($\pm$ 2°F); the use of convection heating or cooling insured against local variations in specimen temperature such as may go undetected when radiant heating is used.

For fatigue tests at elevated temperature, a metal enclosure surrounded the coupon test region, Figure 6. The ovens had front and back water bays and were internally heated using thermal rods. Hot steam escaped from the bays through access holes to the test chamber. Excess condensed water escaping from the test chamber was returned to the exterior water supply of the steam generating bays. The water levels within the heated bays was maintained by a float valve arrangement in an exterior water supply. Temperature was controlled by thermocouples attached to the test specimens. The test arrangement functioned properly in that coupon end tab temperatures during fatigue cycling were maintained below 43°C (110°F) while coupon temperature within the gage length was found to be 82.2° $\pm$ 2°C (180° $\pm$ 5°F) except at the tab interface where the temperature dropped to 65°C (150°F). On rare occasion, especially with laminate 2 tension-compression tests, coupon temperatures reached 88°C (190°F) due to excessive fatigue induced heating within the coupon itself. Throughout the fatigue testing, relative humidity was found to be 90 $\pm$ 3%.

2.5.1 Static Tension Test Procedures

Static tension tests were conducted in a 534 kN (120 kip) Baldwin static test machine. All testing was conducted similar to the procedures of ASTM D3039-74. Tests were conducted using MTS hydraulic self-aligning grips. Alignment was assured by using a special exterior fixture attached to the grip assembly. Because coupon width varied only within $\pm$ 0.025-mm ($\pm$ 0.001-in.), the alignment procedure assured end-to-end coupon alignment within ± 0.076-mm (±0.003-in.). A 50.8-mm (2-in.) extensometer was used to record deflection. Testing was conducted at a standard rate of 1.27-mm/min (.05 in./min).
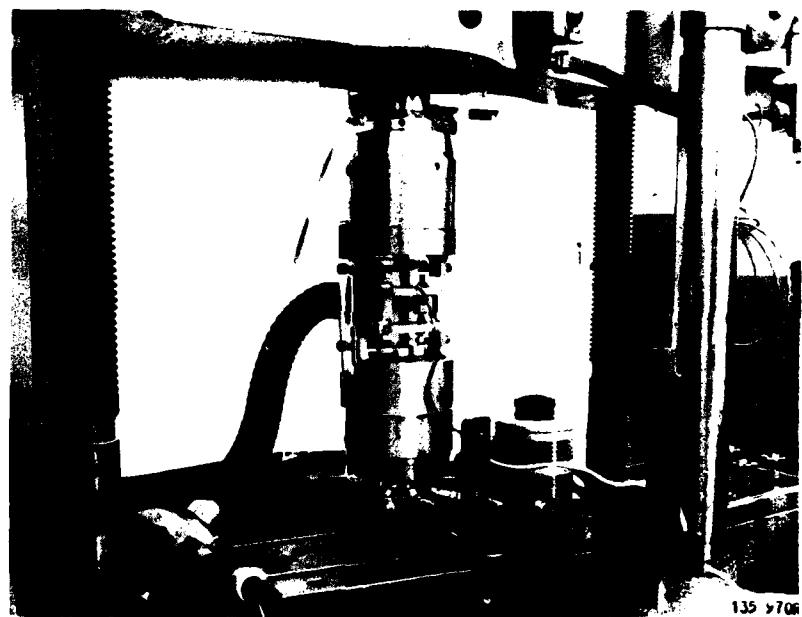
Figure 5. Overall View of Composite Compression Test
Apparatus, with Acrylic Enclosure and Warm
Air Supply

21
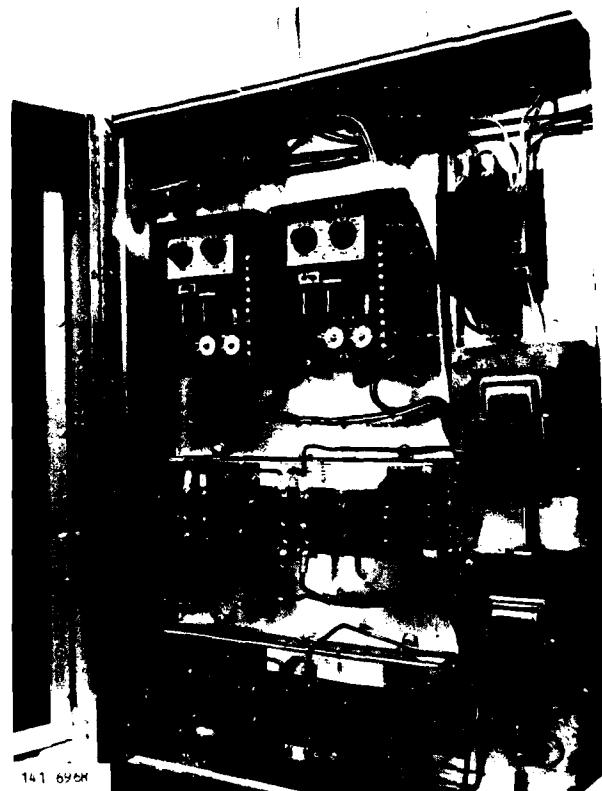
(a)

Environmental
Chamber Electronic
Control System

141 696R
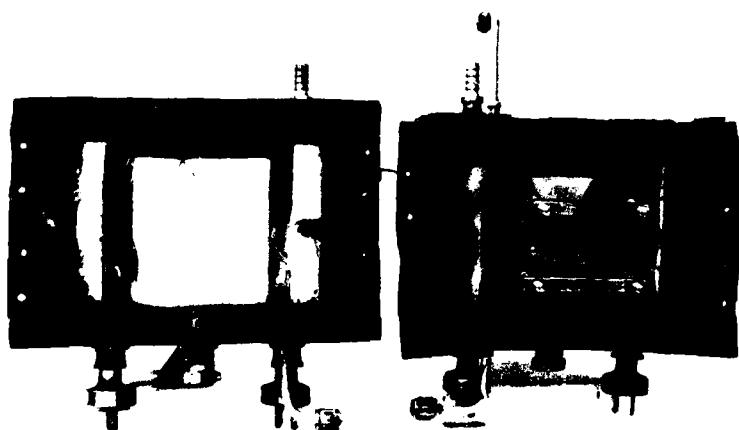
(b)

Environmental
Chambers

141 695R

Figure 6. Environmental Chambers and Associated Control System

2.5.2 Static Compression Test Procedures

The test procedure selected for static compression strength determines this property in the fully constrained mode for a large gage length coupon. This selected method enabled the same coupon geometry used in static tension and for fatigue testing to be used for static compression. The test results should be thought of in terms of column buckling under compression load in that the test condition consists of the state where the unsupported column length is zero. Thus the test results correspond to an inelastic (fully constrained buckling) failure mode. In graphite/epoxy composites, this failure mode is often assumed to be elastic and brittle and thus corresponds to the "true" compression strength and should be equivalent to the tensile strength. In practice, the composite responds inelastically in a manner not dissimilar to the macroscopic behavior of metals loaded in compression. Therefore, no ultimate compression strength exists for composites any more than for metals. Compression strength is dependent on test constraint and thus reflects the inelastic properties of the matrix and the tendency of the fibers to buckle locally. Final fracture has a brittle-like appearance, but should be thought of as an elastic/plastic phenomena.

Static compression tests were conducted using the same 534 kN (120 kip) Baldwin static test machine used for the tension tests. Tests were run at a "static" stroke rate of 1.27-mm/min (.05-in./min). A complete set of test fixtures was developed at Lockheed [7] which permit compression testing of composite laminate specimens under controlled conditions in either the fully-restrained mode, under column compression at various different pin-end lengths, or which can be used with fatigue buckling guides. The specimen-supporting fixtures are designed for use with MTS hydraulically-actuated grips. A full description of these test fixtures is given in Reference 7.

Installation of the modified hydraulic test grips in a universal test machine is shown in Figure 7. A close-fitting steel shell surrounded each grip providing a mount for transverse adjustment screws that prevented destabilizing motion of the platens and specimen. The grips were rigidly mounted to the
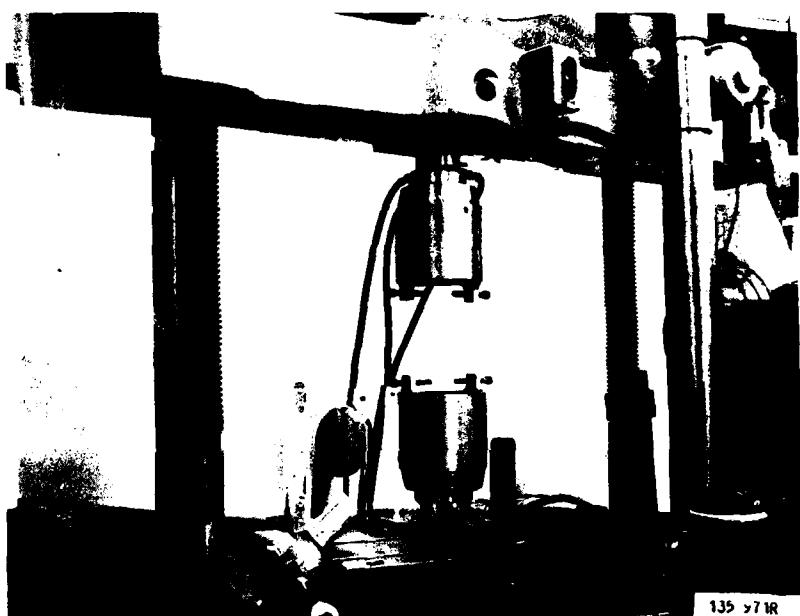
Figure 7.   Installation of Modified Hydraulic Grips
in Universal Testing Machine

machine base and test head, precise alignment having first been achieved with the aid of spherically surfaced seats. Also shown in the photograph is a specimen positioning device, whose function is illustrated in Figure 8. The use of this device assured location of the specimen on the load axis of the grips to within 0.13-mm (0.005-in.).

The fixture used to provide specimen support for testing to zero column length "compression ultimate" stress is shown disassembled in Figure 9. The fixture consists of two rigid guides or platens like those used by Ryder and Black [8] and similar in form to those of ASTM Test for Compressive Properties of Rigid Plastic (D 695-77) (Federal Test Standard 406). On the inner surfaces of the platens are located a set of extendable auxiliary platens which provide support over the full length of the test specimen. The auxiliary platens have a tapered overlap in the width dimension so that no critical length of the specimen is left unsupported. Access holes are provided for extensometer points of 50.8-mm (2.0-in.) gage length, or for electrical strain gages of 1.583-mm (0.0625-in.) length.

In Figure 10 the platens are shown assembled to a specimen which is installed in the grips. The four assembly screws were brought finger-tight providing light pressure between the platens and the specimen. Under these conditions, only a few pounds force was required to cause slippage of the entire platen assembly on the specimen. Exploratory tests have been conducted with the assembly screws tightened with a torque of as much as 1.13 N·m (10.0 in.-lbs), without producing detectable variation in the test results [7]. The installation was completed by bringing the large transverse restraining screws into light contact with the external platens. Figure 11 shows the installation of the extensometer used with this equipment. This instrument, which is of Lockheed-California Company design [9], utilizes a microformer sensor to provide a strain signal for conventional load-strain recording apparatus.

2.5.3 Fatigue Test Procedures

Fatigue testing was accomplished using closed-loop, electro-hydraulic, servo controlled, testing machines of various capacities from 89 to 220 kN (20 to

135 973R
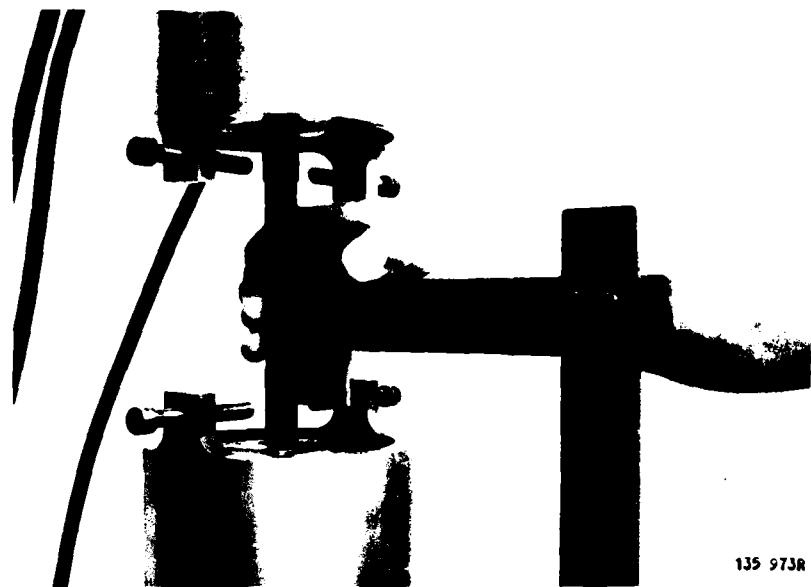
Figure 8.   Specimen Positioning Device

135 996R
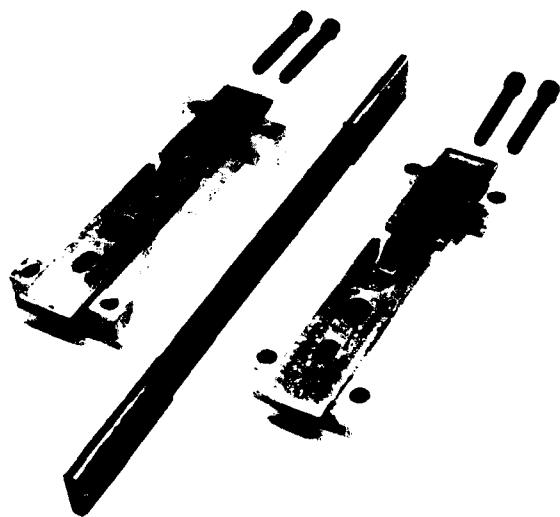
Figure 9.   "Full-Fixity" Apparatus, Showing Auxiliary Platens

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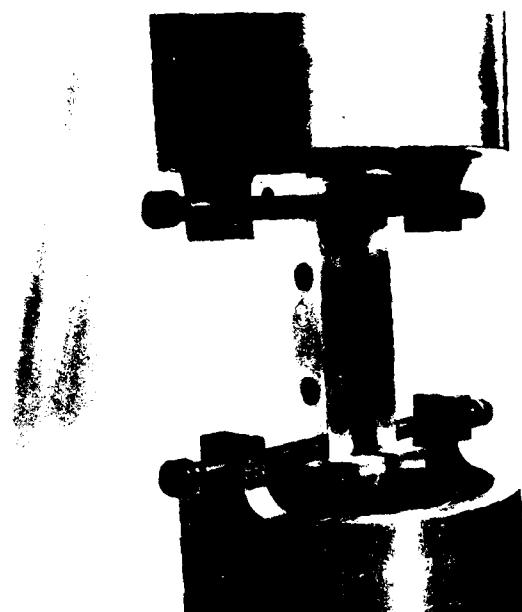
Figure 10.   Specimen and Restraint Fixture Installed in Grips
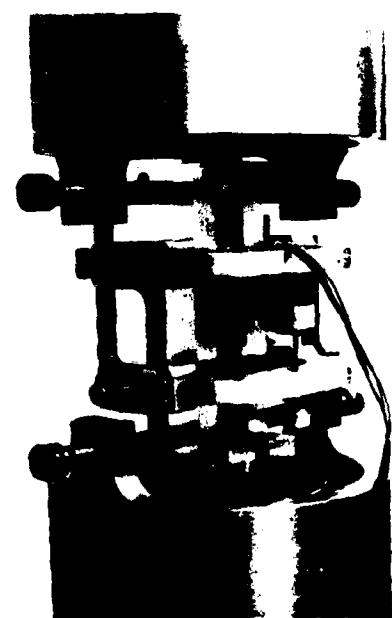
Figure 11.   Installation of Lockheed Extensometer

50 kips) maximum allowable load. Each machine was equipped with a peak and valley load monitoring system which allowed continuous monitoring of the load signal maximum peak, maximum valley, and minimum peak and minimum valley such that load accuracy was maintained within ± 1.0% of the full-scale reading. Fatigue grips were of the friction bolt type with integral alignment fixtures, see Figure 12. Coupon alignment was maintained within ± 0.0762-mm (± 0.003-in.) in any direction. All tests were conducted at 10 Hz. Figure 13 shows a typical tension-tension fatigue test set up and coupon failure. Minimum load in tension-tension (T-T) fatigue tests was approximately 200N (50 lbs.).

Tension-compression (T-C) fatigue tests were conducted using two buckling guide fixtures for stiffness, see Figure 14. Stiffening fixtures were used instead of a fully restrained fixture so that coupon fatigue life under T-C loading would be sensitive to delamination which is the principal mode of macroscopic fatigue induced damage. Two stiffening fixtures were found to significantly increase the buckling stability of a coupon while in the fatigue grips compared to one fixture. However, the use many as six fixtures compared to two was found not to appreciably change the buckling load. More than six fixtures could not be physically placed within a coupon gage length while use of a full constraint defeated the original intent. Therefore, two stiffening fixtures were chosen for use in each T-C fatigue test.

The two guide fixtures were spaced 50.8-mm (2-in.) apart had teflon tape on the faces towards the coupons and had tie-down nuts which were torqued to a approximately 0.224 N·m (2-in. lbs). The maximum compression load for T-C tests was chosen as that compression stress at which the maximum coupon out-of-plane deflection within the gage length exceeded 0.0254-mm (0.001-in) with stiffeners attached.

A chosen minimum load was held constant during the tension-compression fatigue test program of each laminate while the effect on coupon life of different maximum stresses was evaluated. This procedure allowed direct comparison to
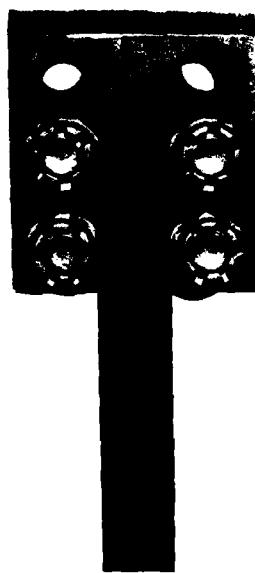
Figure 12. Fatigue Grip

Figure 13. Tension-Tension Fatigue Test Showing
Failed Laminate 1 Coupon
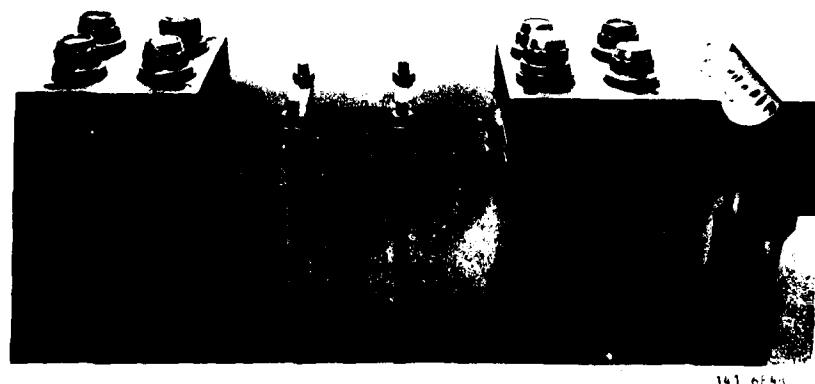
Figure 14. Tension-Compression Fatigue Test Showing
Single Buckling Guide

results previously reported [1]. Other alternatives to holding the minimum load constant, such as constant mean stress or stress ratio, were discarded because the maximum load in tension would have been related to the maximum compression load obtainable which was restricted by buckling of the coupon. Thus, as the maximum load was reduced, the amount of compression would also be reduced. Holding the minimum load constant appeared to be the better alternative because the compression load that could be obtained was maximized within the practical limits of the test. The action of using additional buckling constraints was also examined but rejected because of the possibility of masking the fatigue behavior due to an excessive number of lateral constraints.

Fatigue tests were conducted by first dialing to the calculated mean load and setting the amplitude control such that the maximum load was approximately equal to 95% of the desired maximum load. Five or less cycles were then applied and the load time history recorded on high speed visicorders. This eliminated any possibility of a first cycle load overshoot and allowed the load at failure to be recorded for any first cycle failure coupon. The span control was subsequently increased such that minimum and maximum load were those desired. The peak and valley controls shutdown the fatigue loading and returned the load to the mean value if any load deviations beyond 1/2% were detected.

2.6   DATA ANALYSIS

For fatigue resistant design, one of the major questions concerning application of damage tolerance concepts is specification of percent levels of probability of survival. This question arises because of the need to translate reliability and confidence measures of data to parallel ones for design requirements [11]. In fatigue, reliability can often be successfully defined in terms of the Weibull survivorship function. All of the test data results were statistically analyzed and compared. Primary emphasis was on examining the statistical distribution of static strengths, fatigue lives and residual strengths using a Weibull [10] distribution.

2.6.1 General Discussion of Weibull Function

In Weibull's representation of the statistics of fatigue, there are two random variates at each stress test condition. The first of these variates is the ordered sequence of the numbers of cycles to failure for each test result, n_i.

$$n_i: (n_1, n_2, n_3 \ldots n_N)$$

The second random variate, x, is continuous and is the argument of the Weibull survivorship function, or probability of survival, expressed at

$$P(x) = \exp \left[-\left((x-e)/(v-e) \right)^k \right] , \tag{1}$$

where $\quad x \geq e, \; v \geq e, \; k > 0, \; P(e) = 1, \; P(v) = 1/\exp(1).$

The connection between the random variates, n_i and x, is entirely empirical. In practice, numerical procedures are used to derive the three Weibull parameters k, e, and v by means of the approximation

$$P(x) = 1 - i/N \text{ when } x = n_i. \tag{2}$$

$$\text{or} \qquad P(x) = 1 - i/(N + 1)$$

For equation (1), the mean of the sample set is given by [9]:

$$\bar{x} = e + (v-e) \; \Gamma \; (1 + 1/k) \tag{3}$$

the median by:

$$x = e + (v-e) \; (\text{Log}_e 2)^{1/k} \tag{4}$$

and the mode by:

$$\tilde{x} = e + (v-e) \; (1 - 1/k)^{1/k} \tag{5}$$

where Γ ( ) indicates the incomplete Gamma function.

During the past twenty-five years, a number of names have been applied to the parameters. In general, parameters e and v are scale parameters or factors while the exponent k is a shape parameter. Some confusion has resulted in the literature by referring to scale parameter e as the minimum life esti-mate. With this choice of words, e is often suggested on physical grounds

to be $e \geq 0$. Many authors have reasoned further that since $e \ll n_i$, $i = 1$, 2, 3, ... N, the Weibull survivorship function can be appropriately reduced to dependence on two parameters, k and v, with $e = 0$ arbitrarily. An argument against this practice is described below. Often, the term threshold parameter is applied to parameter e and the term characteristic value to v. In analysis of composite data, k is often denoted by α and v by F.

The influence of the shape parameter k can be explained as follows. Define a reduced variate Z as:

$$Z = (x-e)/(v-e), \quad Z \geq 0, \text{ dimensionless,} \tag{6}$$

and express the probability of survival function as:

$$P(x) = \exp\left[-Z^k\right], \quad k > 0, \tag{7}$$

where $\quad P(Z) = 1/\exp(1)$ when $Z = 1$,

and $\quad\quad\quad P(Z) = 1 \quad\quad$ when $Z = 0$, for all k.

If $k < 1$, this implies the test specimen material develops resistance to fatigue as the number of load cycles is increased. If $k = 1$, the Weibull survivorship function reduces to the constant failure rate relation commonly used in reliability studies. If $k > 1$, one can inquire whether the test specimen material experiences progressive damage as numbers of load cycles are increased.

Figure 15 illustrates the manner in which P(Z) is dependent on the shape parameter k for the range of the reduced variate Z from zero to two. Empirical evidence does not support the interpretation that k might be a smoothly increasing function of stress amplitude. For practical purposes, in the case of structural fatigue, the region of Figure 15 of most interest to designers is bounded as follows:

   (a) Above by the limit $P(Z) = 1.0$
   (b) Below by the median $P(Z) = 0.5$
   (c) On the left by the curve $P(Z) = \exp[-Z]$
   (d) On the right by the curve $P(Z) = \exp[-Z^{-10}]$.
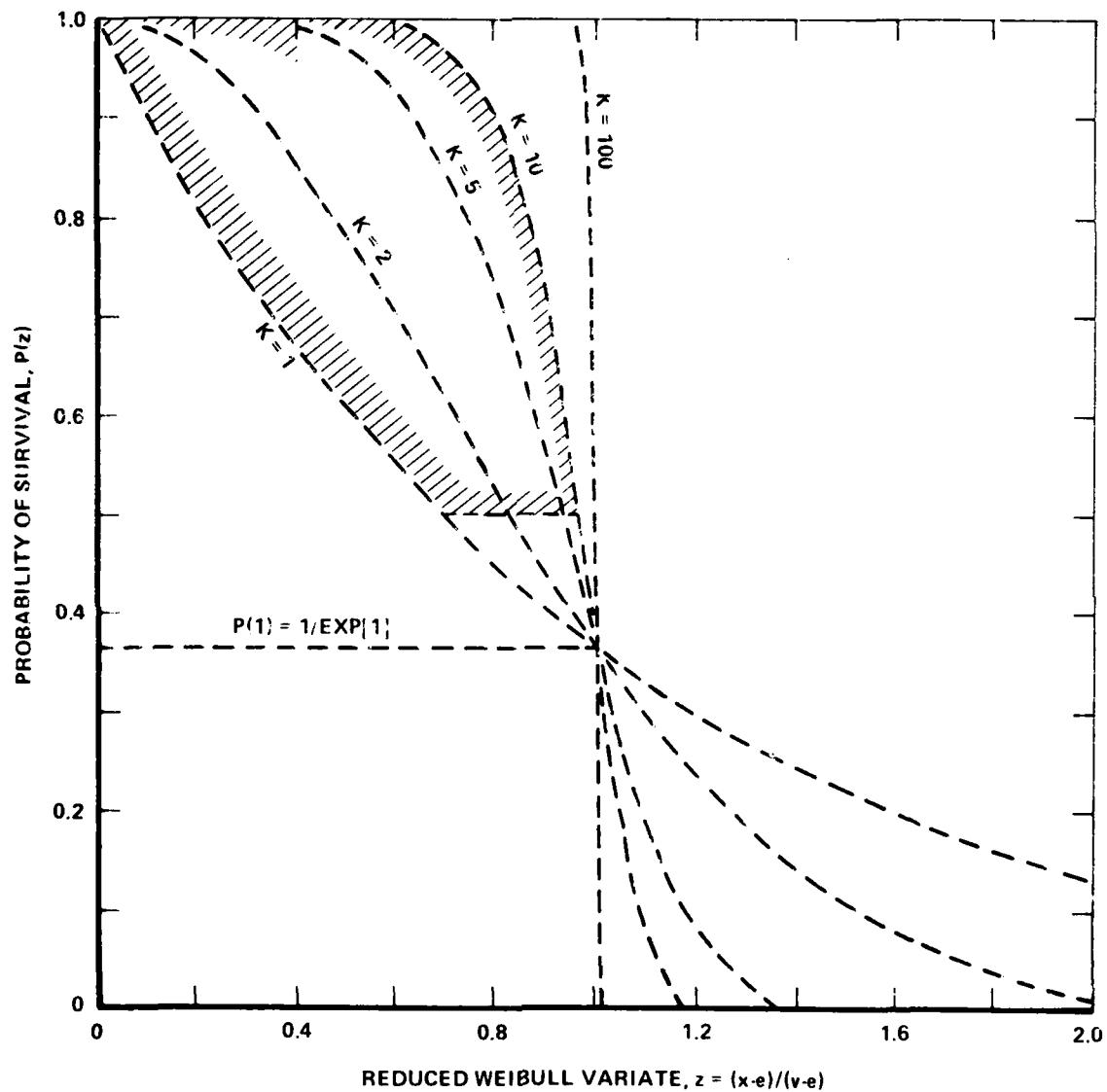
Figure 15.   Influence of Shape Parameter k on Probability of Survival

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2.6.2   Weibull Analysis Procedures

There are three principal procedures which have been used to determine the
Weibull parameters, k, e, and v for a given data set. These are: the
moment estimation (ME) method; the maximum likelihood estimation (MLE) pro-
cedure; and some form of the linear regression (LR) procedure. All three
methods are also used to determine the unknown parameters of other types of
fitting functions. The ME method principally consists of equating several
population moments (equal to the number of unknown parameters) to the sample
moments. The MLE method consists of setting the partial derivatives of the
logarithm of $P(X)$ with respect to the parameters sought equal to zero. In
the LR procedure, the Weibull survivorship function is reduced to a linear
equation. For the LR method, the solution for a two-parameter Weibull func-
tion is straight forward, but in the three-parameter case the correct solu-
tion is found by optimization of the correlation coefficient or by matching
the sample skewness coefficient.

When one of the above described procedures was originally selected [1] for
analyzing graphite/epoxy composite strength and fatigue data, consideration
was given to two thoughts. First, how well does the resultant Weibull sur-
vivorship function represent the original data set ? Second, what extra-
polative potential exists for the resultant function, if any ? Consideration
of these two questions led to the selection of the LR procedure. The reasons
for this selection will be described in detail along with references to
recent work which supports the original choice.

Both the ME and MLE methods require homogeneous samples. The reason for this
requirement is that in the ME procedure the Weibull density function is in-
tegrated while in the MLE procedure, partial derivatives of the function are
obtained. Both integration and differentiation processes require homogenous
samples. This requirement of homogenaity was not assumed a priori, to be
necessarily met by sample information obtained from fracture data of composites
A procedure was desired which would be sensitive to the possible existence
of multi-component strength and fatigue life data. Such a requirement appears
to be met by a LR procedure [12]. The ME method results in significant

errors in estimation of k, e, and v [12]. Such errors increase as k increases [12]. In the case of two-parameters, errors in estimation of k and v increase linearly with the true value of e (assumed to be zero) and can be greater than 100% when e ≥ v [12]. For the MLE procedure, three difficulties are encountered. First, the MLE solution of a data set is often a local maximum, but is not the maximum likelihood estimate [12-16]. Weibull and Weibull [13] found in a study of 300 random samples of 10 and 20 points each that approximately half of the estimates were not the maximum likelihood estimate, but were local maximums. Second, valid data sets can occur for which convergent solutions are not forthcoming, particularly for three parameter solutions [16]. Third, if a given data set which actually belongs to a three parameter Weibull population is assumed to be a two-parameter population (e = 0), the estimates of k and v can be significantly higher than their true values [12].

In the analysis of graphite/epoxy composite data, the parameter e is often set equal zero. This practice greatly simplifies the mathematics especially for MLE procedures; however, there are strong objections against such a practice [10, 12, 16]. These have already been discussed with reference to the ME and MLE procedures and are based upon the statistical error induced by the practice of setting e = 0. In summary, the three-parameter Weibull fit can be shown to fit the actual data set better than the two-parameter [1, 12, 16]. However, objections against the three-parameter Weibull fitting procedure are often raised upon the grounds that the parameter e may be found to have a negative value, particularly for a fatigue data set.

The objection is thus raised that actual coupons can not have a finite probability of failure when the applied load is zero. Setting e equal to zero appears to solve this problem. This practice is principally related to the question of the extrapolative capability of the Weibull function for graphite/epoxy composite fracture data.

Setting e = 0 results in the probability of survival, P_s, being equal to 1 when no load is applied to a coupon. While this is a reasonable expectation,

the loss of fitting accuracy in the range of the data is sacrificed. At
the same time, the resultant extrapolative estimates of strength and
fatigue life at $F_s > 0.90$ may still be intolerably conservative. Therefore,
by setting $e = 0$ we have gained little if anything and lost much. This
problem is most critical for fatigue life.

The problem of correctly extrapolating composite fatigue data is presently
one of conjecture. This is due to three reasons: lack of; 1) large labora-
tory data sets for evaluating extrapolation from small subsets; 2) experi-
mental data which correlates laboratory coupon results with structural test
results; 3) field service experience. Therefore, while in a realistic sense,
e should be greater than or equal to zero, correct values can not be deter-
mined at this time. Thus, forcing $e = 0$ leaves us in the unenviable position
of reducing the accuracy of our calculated fit to the data set and most
likely being too conservative in our extrapolative predictions.

A possible solution to these problems has been suggested by Bowie, Besari,
and Trapp [16] and will be discussed below. For the present, a three-para-
meter Wiebull analysis procedure has been used throughout this report. The
resultant analytical solutions closely fit the data and avoid the problems
of ME and MLE solution procedures. The resultant functions are not of extra-
polative value, but this is not of pertinence for the comparison of data
sets. Significant statistical analysis effort combined with extensive experi-
mental investigations are needed before any extrapolative procedure can be
developed and used with confidence. Hence, using a procedure which does not
allow for extrapolation is not considered at the present time to be detrimental
since no such procedure is presently available.

2.6.3 Description of Selected Analyses Procedure

The particular form of Weibull analyses used in this report is based upon
the work inspired by G. E. Bowie [11, 16]. Essentially, this procedure which
consists of linear regression analysis in Z variate space, is similar to
that used by Talreja [12]. The analysis procedure used will be described in

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detail to reduce the possibility of misunderstanding.

In the analytic procedure used in this program, an initial estimate was made
of the probability of survival based directly on the test results, in a
staircase manner, $P(n_i)$, $i = 1, 2, 3, \ldots N$,

where: $P(n_1) = 1-1/N$

$P(n_2) = 1-2/N$

$P(n_3) = 1-3/N$
$\vdots \qquad \vdots$

$P(n_N) = 1-N/N = 0$.

The function $P(n_i) = 1 - i/N$ was selected instead of the alternate function,
$P'(n_i) = 1 - i/(N+1)$. The difference $(P'(n_i) - P(n_i))$ diminishes as N is
increased. Thus for N equal to or greater than approximately 15, as in this
investigation, the difference is undetectable. However, if extrapolations to
probability of survival in the range above 90% are to be attempted, the
choice of $P(n_i)$ rather than $P'(n_i)$ as initial distribution is the more con-
servative approach [11]. This is especially true for N less than 15.

With the above approach, the initial distribution is defined as:

$P(n_i) = 1 - i/N$

and $P(n_{i+1}) = 1 - i/N$ if $n_{i+1} = n_i$

otherwise $P(n_{i+1})/ 1 - (i +1)/N$

In the past, other workers used the choice $P'(n_i) = 1 - i/(N+1)$ as the initial
description without regard to replication of the type: $n_{i+1} = n_i$. The choice
of assigning the same initial probability to different coupons with the same
n_i was considered appropriate because they do actually form a local mode,
within the limits of testing accuracy, of the sample distribution obtained
by experiment.

The appropriate variables of Equation 1 are found by forming N-1 relations:

$$P(n_1) = 1-1/N = \exp\left[-((n_j-e)/(v-e))^k\right]$$

$$P(n_2) = 1-2/N = \exp\left[-((n_i-e)/(v-e))^k\right] \tag{8}$$

$$\vdots \qquad \vdots \qquad \qquad \vdots$$

$$P(n_N) = 1-N-1/N = \exp\left[-((n_{N-1}-e)/(v-e))^k\right]$$

The last relation for N is not used since $P(N) = 0$.

The parameter of Equation 1 were found by reducing the relationships of Equation 8 to the linear equation:

$$Y = bX+a. \tag{9}$$

The three-parameter Weibull linear equation is:

$$\left[-\ln P(X)\right]^{1/k} = bX+a, \tag{10}$$

where $e = -a/b$

and $v = (1+be)/b$.

For the two parameter Weibull function ($e = 0$), the linear equation is:

$$\ln(-\ln(P(X))) = b\ln(X) + a, \tag{11}$$

where $k = b$

and $v = \exp(-a/b)$.

A linear regression method is used to determine k, e. and v. The initial order distribution is:

$$P(X_i) = 1-i/N_p, \quad i = 1, 2, 3 \ldots N_p. \tag{12}$$

Regression coefficients are found by least square analysis of N_p-1 equations such as:

$$\left[-\ln(1-i/N_p)\right]^{1/K} = bX_i + a, \quad i = 1, 2, 3 \ldots N_p-1. \tag{13}$$

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The sample correlation coefficient, R, is calculated as well as:

$$R = \frac{M \sum_{i=1}^{M} Y_i (aX_i = b) - \sum_{i=1}^{M} Y_i \sum_{i=1}^{M} (aX_i = b)}{\left[\left\{ M \sum_{i=1}^{M} Y_i^2 - \left(\sum_{i=1}^{M} Y_i\right)^2 \right\} \left\{ M \sum_{i=1}^{M} (aX_i = b)^2 - \left(\sum_{i=1}^{M} (aX_i = b)\right)^2 \right\} \right]^{1/2}}$$

where $M = N_p - 1$

The coefficients of linear regression and alternative correlation coefficient r are calculated by means of the following steps:

$$Sx = \left[\frac{M \sum_{i=1}^{M} X_i^2 - \left(\sum_{i=1}^{M} X_i\right)^2}{M(M-1)} \right]^{1/2}$$

$$Sy = \left[\frac{M \sum_{i}^{M} Y_i^2 - \left(\sum_{i=1}^{M} Y_i\right)^2}{M(M-1)} \right]^{1/2}$$

$$b = \frac{M \sum_{i-1}^{M} X_i Y_i - \left(\sum_{i=1}^{M} X_i\right) \left(\sum_{i-1}^{M} Y_i\right)}{M \sum_{i-1}^{M} X_i^2 - \left(\sum_{i=1}^{M} X_i\right)^2}$$

$$a = \left(\alpha \sum_{i=1}^{M} Y_i - b \sum_{i=1}^{M} X_i \right) \bigg/ M$$

$$r = b\, Sx/Sy$$

The standard deviation of the linear regression is calculated by means of the expression

$$s = \left[\frac{(M-1)}{(M-2)} \; Sy^2 \; + \; (1 - r^2) \right]^{1/2}$$

The values of k, e, and v are found by iterating on 1/k in Equation 13 and maximizing R in Equation 14. An alternative procedure would be to match the sample skewness to the Weibull function skewness by iteration of 1/k. The coefficient of skewness is given by:

$$= \frac{\Gamma(1+3/k) - 3\Gamma(1+1/k)\,\Gamma(1+2/k) + 2\Gamma^3(1+1/k)}{(\Gamma(1+2/k) - \Gamma^2(1+1/k))^{3/2}} \tag{15}$$

and recalling that $\Gamma\,(\;)$ denotes the incomplete Gamma function.

There are two primary difficulties with the method employed. First, the resultant Weibull functions could be used to imply that in some three-parameter cases and at a given extrapolated high probability of survival ($P_s > 0.95$), fatigue life decreases as applied stress amplitude decreases. Second, in the case of two-parameter analysis, probability of survival functions tend to predict overly conservative extrapolated fatigue lives, particularly at low applied stress amplitudes. Both of these difficulties refer to the extrapolative capability of the resultant functions. This is not considered a problem for comparing the data sets, and as discussed in Section 2.6.2, extrapolation of the data does not appear to be presently feasable.

2.6.4   Alternative Procedures

Two other procedures are available for analyzing fracture data which were not known at the time of the original investigation [1], but are of interest. They are the Standardized Variable Estimation (SVE) method [12] and the Modified Double Exponential Function (MDEF) method [16].

In the SVE method [12] the standardized variable Z is defined as in Equation 6 for a Weibull survivorship or as $Z = \dfrac{X-e}{v}$ $\tag{16}$

for a Weibull probability of failure function. Thus, as mentioned in Section 2.6.1, the order statistics Z_i are independent of e and v and depend only on the shape parameter k. The expected value, EZ_i, median, MZ_i, and variance, VZ_i, of the order statistic Z_i were derived by Lieblein [17]. The characteristic values of Z_i depend only on the sample size, N, and the shape parameter, k [12]. From Equation 16, we obtain [12]:

$$X_i = e + v\ EZ_i \tag{17}$$

$$\text{or} \qquad X_i = e + v\ MA_i . \tag{18}$$

Equations 17 and 18 can be solved by linear regression. The shape parameter k is the value for which the correlation coefficient is a maximum [12]. The parameters e and v are found as the X_i - intercept and slope of the best fit line [12]. If the sample data belongs to different populations, this will result in the $(X_i,\ EZ_i)$ and $(X_i,\ MZ_i)$ scattering about different straight lines [12].

Talreja [12] found that the SVE method provided accurate estimates of k, e, and v for low values of k. At higher k values, the method often gives negative estimates of e. The procedure gave more accurate estimates of the parameters than the ME and MLE methods [12].

The MDEF is based upon the double exponential function of Gumbel [10]. In this procedure [16], for a set of sample fatigue lines, N_p, the initial distribution is defined by:

$$P(X_i) = 1 - i/(N_p + 1) \tag{19}$$

$$\text{and} \qquad P(X)\ \text{by:}$$

$$P(X) = 1 - \text{Exp}\ [-\text{Exp}[-\alpha_0\ (X-u)]] . \tag{20}$$

For lives greater than u, the above function is used as described by Gumbel [10]. For lives less than u, α is a function of the life, X,

$$\text{where} \qquad \alpha(X) = \alpha_0\ \frac{\ln u - \ln X_0}{\ln X - \ln X_0} . \tag{21}$$

The parameter X_0 is defined as the threshold fatigue life. For $X \leq X_0$, P_S is defined as equal to unity. Details of this procedure are described in Reference 16.

The modified double exponential function (MDEF) can be solved by ME, MLE, or LR procedures. The best procedure appeared to be linear regression [16]. The MDE function was found to not only fit the sample data with high correlations but to provide procedures for exploration of data extrapolation accuracy.

SECTION III

MATERIAL CHARACTERIZATION

The T300/934 graphite/epoxy material used in this program had a fiber tensile strength considerably higher than those used previously [1]. A comparison of the T300 fiber properties is shown in Table 3. Because of the increased fiber strength (~ 7%) of the material used in this investigation compared to that previously used, an increased laminate strength was anticipated.

From the received graphite/epoxy prepreg, eleven (11) panels of laminate 1 and five (5) of laminate 2 were manufactured. The panel numbers are listed in Table 4.

Resin, fiber, and void analysis results of laminate 1 panels are given in Table 5 and those of laminate 2 in Table 6. The fiber volume testing was conducted by Delsen Testing Laboratories, Inc., Glendale, California in accord- and with ANSI/ASTM B-3171-73, Procedure A, entitled "Fiber Content of Rein- forced Resin Composites" except as noted below:

(a) Determinations for each strip of material were carried out in triplicate (see Figure 16 for location of test specimens)

(b) Specimen size was approximately 1 gm rather than 0.3 gm

(c) The volume of Nitric Acid used for digestion was increased from 30cc to 100cc because of the larger specimen size.

The specific gravity testing was conducted in accordance with ANSI/ASTM D-792- 66, Procedure A-1: "Specific Gravity and Density of Plastics by Displacement." Tables 5 and 6 clearly show the consistency of the panels, but also show that their fiber content by weight is higher than those reported in Reference 1 by the same amount for both laminates. This resulted in thinner panels than those fabricated previously.

TABLE 3

T300 FIBER PROPERTIES

Fiberite Lot No.	Fiber Density, g/cc	Fiber Tensile Strength MPa(ksi)	Fiber Modulus GPa(psi x 10^6)	Lockheed Lot I.D.	Laminates Material Used on and Associated Contract
80-2	1.760	2654 (385)	227.5 (33.0)	MJ	Laminate 1[a]
112-2	1.750	2537 (368)	233.0 (33.8)	NH	Laminates 1[a] & b and 2[a]
6-C-73	1.758	2840 (412)	223.4 (32.4)	SF	Laminates 1[b] and 2[b]

[a] - Material used on Contract F33615-75-C-5118, data reported in AFML-TR-76-241

[b] - Material used on present Contract F33615-77-C-5045

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TABLE 4

IDENTIFICATION NUMBERS OF PANELS
USED IN TEST PROGRAM

Laminate 1	Laminate 2
1SF1117	2SF1133
2SF1117	1SF1137
1SF1121	2SF1137
2SF1121	1SF1149
1SF1122	2SF1149
2SF1122	
1SF1130	
2SF1130	
1SF1132	
2SF1132	
1SF1133	

TABLE 5

RESIN, FIBER, AND VOID ANALYSIS RESULTS FOR LAMINATE 1 PANELS

Panel No.	Resin Content, wt. %	Fiber Content, Vol. %	Void[a] Content, V_c %	Density, gm/cc
1SF1117	26.0	67.6	-.04[b]	1.607
2SF1117	26.4	67.1	.02	1.604
1SF1121	25.4	68.3	.04	1.609
2SF1121	26.0	67.4	.21	1.603
1SF1122	25.2	68.6	-.09[b]	1.612
2SF1122	25.1	68.7	-.04[b]	1.612
1SF1130	26.7	67.0	-.12[b]	1.605
2SF1130	26.3	67.5	-.24[b]	1.609
1SF1132	26.4	67.2	.03	1.604
2SF1132	25.6	68.0	.11	1.607
1SF1133	27.0	66.6	-.09[b]	1.603
Avg.	26.0	67.6		1.607
Std. Dev.	0.622	0.683		0.0033
Coef. of Var.%	2.4	1.0		0.21
Avg. Previous Values on MJ Panels [1], Laminate 1	30.4	62.6		

[a] - V_c, void content determined by Standard Chemical Analysis procedures

[b] - Artifact of Chemical Analysis procedure for void content determination.

TABLE 6

RESIN, FIBER, AND VOID ANALYSIS RESULTS FOR LAMINATE 2 PANELS

Panel No.	Resin Content, wt. %	Fiber Content, Vol. %	Void[a] Content, V_c %	Density gm/cc
2SF1133	26.9	66.6	.05	1.601
1SF1137	26.7	66.8	.19	1.604
2SF1137	27.4	66.0	.02	1.599
1SF1149	26.4	67.1	.16	1.602
2SF1149	26.1	67.5	.01	1.606
Avg.	26.7	66.8		1.602
Std. Dev.	0.495	0.561		0.0027
Coef. of Var. %	1.8	.84		0.17
Avg. Previous Values on NH Panels, Laminate 2	31.4	61.8		

[a] - V_c, void content determined by standard chemical analysis procedures
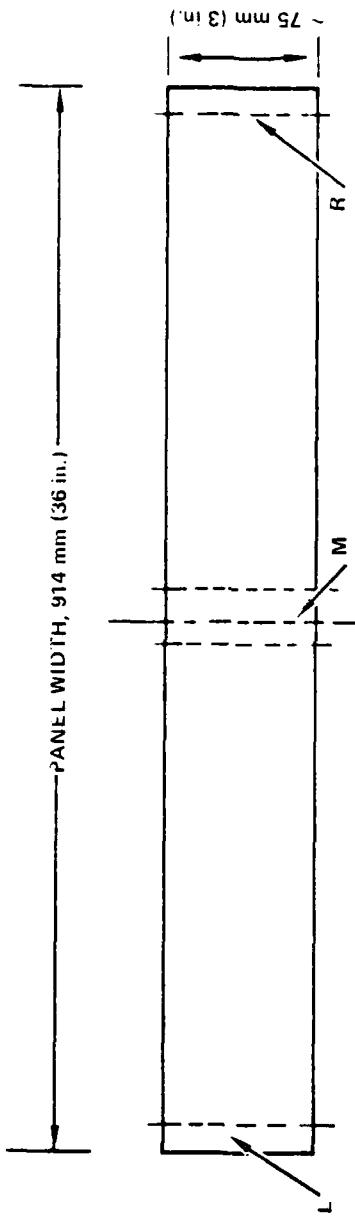
Figure 16. Locations of Three Specimens from each panel used for specific Gravity and Acid Digestion tests.

(Strips taken from center of panel except for 1SF1121, 2SF1121, and 1SF1122, which were taken from one end due to machining error.)

Void contents were obtained by standard chemical analysis procedures which unfortunately result in an error of ± 1.6% in void content; i.e., a calculated result of 2% voids can actually be between 0.4 and 3.6% voids. The error is due to uncertainty in original fiber and matrix density properties and in the amount of absorbed moisture which also affects density. This level of inherent error can result in physically impossible negative void content determination.

The chemical analysis void content determinations combined with the lack of any C-scan indications do imply that the void content of all panels was extremely low, <<1%. Because no C-scan indications were observed in any of the panels, photographs of the C-scan are not included.

SECTION IV

HIGH TEMPERATURE, MOISTURE CONDITIONING

Coupons to be tested statically or dynamically at 82.2°C (180°F), 90% R.H. were conditioned at 82.2°C (180°F), 90% R.H. to essentially equilibrium moisture distribution conditions. Moisture weight gain was measured using 127-mm (5-in.) long by 22.2-mm (7/8-in.) wide traveler coupons cut from the gage section of typical test coupons. Traveler and moisture distribution coupons taken from laminates 1 and 2 test coupons were used in four different groupings. They were:

Group 1: Coupons for initial moisture content and distribution prior to 82.2°C (180°F), 90% R.H. conditioning.

Group 2: Coupons to measure weight gain and moisture distribution changes while being held in the room temperature, 45% R.H. holding chambers.

Group 3: Coupons for measuring weight gain and moisture distribution during conditioning at 82.2°C (180°F) and 90% R.H. and for determining weight gain just prior to static and fatigue tests.

Group 4: Coupons used for determining weight loss and moisture distribution changes which occurred due to static testing.

The results of each of these four groups will be discussed. The moisture distributions given in the following figures were experimentally determined using the procedure of Sandorff and Tajima [18]. All moisture distributions were determined using three samples cut from the traveler test coupon under investigation.

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Group 1: Initial Moisture Content and Distribution

The initial distribution of moisture within representative coupons after all manufacturing and machining operations were complete and before being placed in the room temperature, 45% R.H. holding chamber are shown in Figures 17 and 18. The average weight loss values are those recorded during the dry out process used to determine the moisture distribution. These values are equal to the average weight gain due to moisture with respect to the zero condition. The procedure used to determine the moisture distribution was conducted in such a way to insure that only moisture loss was being recorded during the drying process [18]. The results shown in Figures 17 and 18 show not only a significantly greater initial moisture content for the laminate 1 coupons, but also a much more irregular and less reproducible moisture distribution than for the laminate 2 coupons.

The initial moisture in the coupons after manufacturing and prior to conditioning was also determined by removing coupons during conditioning and subtracting the weight gain from their final moisture content determined by drying. Results are shown in Table 7 and compared to those determined by the moisture distribution process.

Group 2: Weight Gain in Holding Chamber

Three traveler coupons were obtained from both laminates 1 and 2 and used to monitor weight gain due to moisture absorption of the coupons held in the room temperature, $45 \pm 5\%$ R.H. holding chamber. The results of the study are tabulated in Table 8 and show that less than a 0.17% weight gain occurred after one year compared to the initial condition. The moisture distribution within two of these coupons was checked after 385 days and results are shown in Figures 19 and 20. As expected, the only change is that the moisture distributions have tended towards equilibrium, thus raising the average moisture content.

Group 3: Weight Gain and Moisture Distribution Changes due to Conditioning

Coupons were conditioned at 180°F, 90% R.H. in three different chambers which will be called No. 1, No. 2, and No. 3. The reason for using several
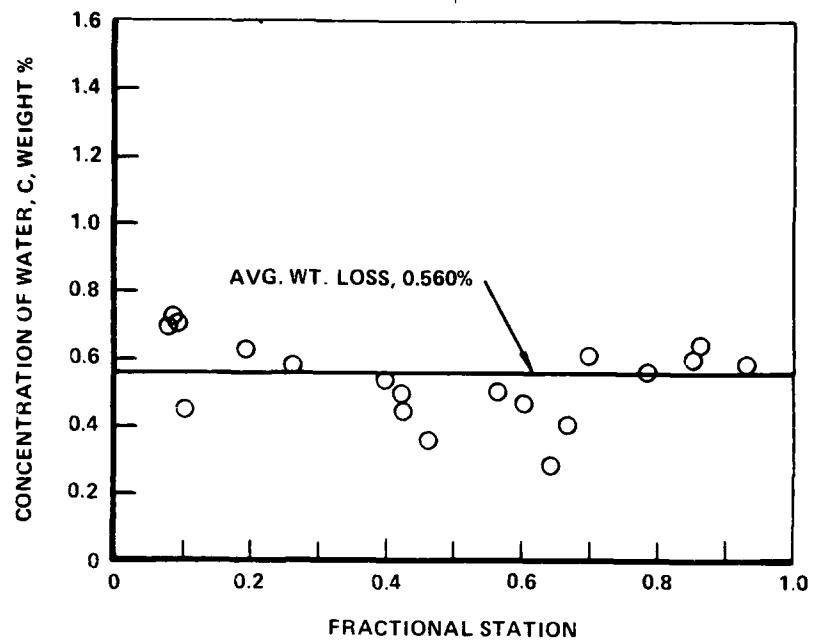
FIGURE **17.** MOISTURE DISTRIBUTION IN LAMINATE 1 COUPON ISF1117-D16 BEFORE
HIGH TEMPERATURE MOISTURE CONDITIONING
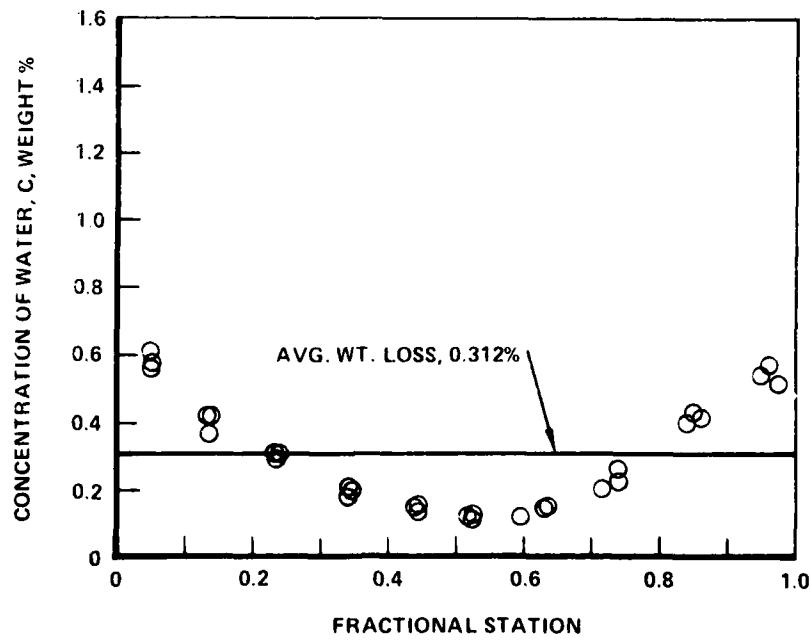
FIGURE **18.** MOISTURE DISTRIBUTION IN LAMINATE 2 COUPON 2SF1133-D28 BEFORE
HIGH TEMPERATURE MOISTURE CONDITIONING

TABLE 7

ESTIMATES OF INITIAL COUPON MOISTURE CONTENT
PRIOR TO CONDITIONING

Laminate	Traveler Coupon ID	Measurement Procedure	Estimated Initial Moisture Content, Weight, %
1	1SF1117-D2	E[a]	.266
	1SF1117-D11	E	.411
	1SF1117-D14	E	.381
	1SF1117-D16	MD[b]	.560
	1SF1117-D17	E	.462
	1SF1117-D21	E	.346
	1SF1117-D25	E	.393
	2SF1117-D2	E	.257
	2SF1117-D20	E	.366
2	2SF1133-B8	E	.114
	2SF1133-C26	E	.297
	2SF1133-D28	MD	.312
	1SF1137-A5	E	.126
	1SF1137-B20	E	.101
	1SF1137-C7	E	.262
	2SF1137-B2	E	.110
	2SF1137-B10	E	.389
	1SF1159-A27	E	.162
	1SF1149-C20	E	.114

a - E; Initial moisture content determined by subtracting
weight gain from final moisture content

b - MD; Initial moisture content determined directly, prior
to high temperature conditioning, by drying of sample.

TABLE 8

MOISTURE GAIN IN TRAVELER COUPONS PLACED IN ROOM
TEMPERATURE, 45 ± 5% R.H. HOLDING CHAMBER

Values are % Weight Gain

Days After Placement in Chamber	Laminate					
	1			2		
	Coupon ID			Coupon ID		
	1SF1117-D17	1SF1117-D20	2SF1117-D22	2SF1137-D32	2SF1137-B10	2SF1149-C27
0	0	0	0	0	0	0
15	.0176	.0155	.0174	.0125	.0240	.0169
28	.0274	.0280	.0299	.0263	.0331	.0279
42	.0450	.0435	.0444	.0381	.0461	.0390
56	.0528	.0580	.0608	.0480	.0565	.0481
70	.0724	.0764	.0791	.0644	.0727	.0611
84	.0821	.0841	.0868	.0710	.0799	.0643
99*	.0782	.0832	.0878	.0717	.0825	.0688
112*	.0831	.0725	.0762	.0730	.0786	.0649
127	.1037	.0967	.1032	.0920	.0994	.0831
141	.1076	.0957	.1032	.0901	.1020	.0831
170	.0968	.0958	.1032	.0927	.1052	.0851
200	.0978	.0996	.1052	.1025	.1110	.0909
228	.1095	.1093	.1216	.1118	.1208	.0987
256	.1115	.1132	.1264	.1124	.1227	.1020
287	.1193	.1190	.1322	.1196	.1299	.1091
315	.1271	.1296	.1418	.1288	.1390	.1156
345	.1408	.1518	.1534	.1385	.1487	.1260
371	.1477	.1509	.1621	.1453	.1559	.1344
385	.1496	.1548	.1650	.1466	.1604	.1370

* During one two-week period the chamber conditions decreased before the chamber
was repaired. This is reflected in slight drop in moisture content.

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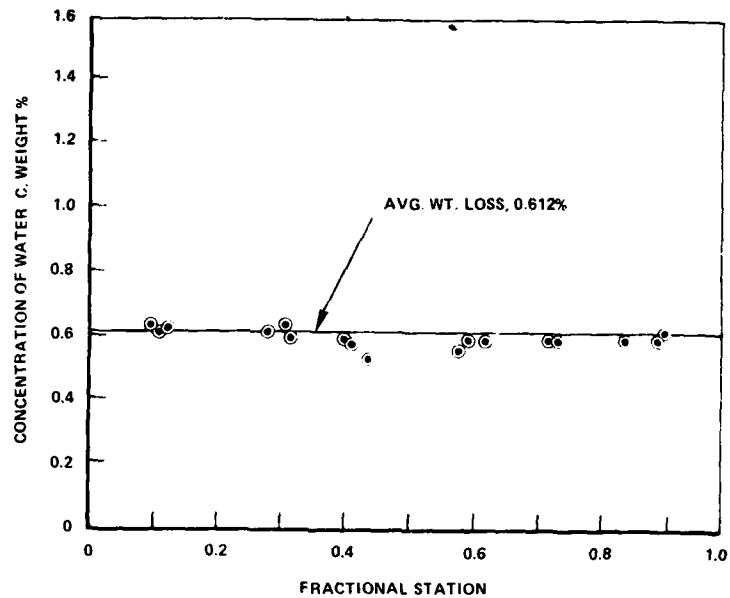
Figure 19.   Moisture Distribution in Laminate 1 Coupon 1SF1117-D17 after 385 Days Storage at Room Temperature and 45 ± 5% R.H.
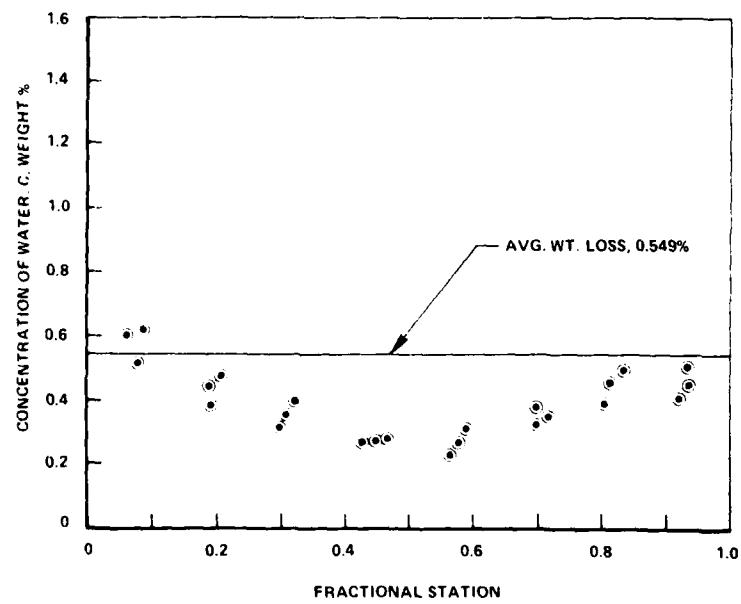
Figure 20.   Moisture Distribution in Laminate 2 Coupon 2SF1137-B10 after 385 Days Storage at Room Temperature and 45 ± 5% R.H.

chambers was due to the failure of chamber No. 1, malfunctions in chamber No. 2, and the size limitations of chamber No. 3. Conditions within each chamber were tracked by weight gain traveler coupons which accompanied each set of test coupons placed in the chamber. Since differences in equilibrium moisture contents were detected using the traveler coupons, the weight gain data was carefully scrutinized. This was necessary because differences in fatigue properties were observed due to the different moisture contents. The effects on fatigue life are discussed in Section 6.3.

The mechanical tests conducted using Coupons conditioned in Chamber 1 were: Laminate 1 un-notched static and S-N fatigue; laminate 2 un-notched static and S-N fatigue. Figures 21 and 22 show the moisture distribution within representative coupons after 63 days of 82.2°C (180°F), 90% R.H. conditioning while Figures 23 and 24 show the distribution at 127 days. These figures show that essentially an equilibrium moisture distribution was obtained between the 63 and 127th day of conditioning.

Table 9 shows the weight gain data for Figures 21 to 24 in tabulated form. Considering the zero day moisture content as a baseline, Table 9 shows that weight gain among the various traveler coupons was quite consistent within a laminate type. This was consistent for all traveler coupons which were started as a group.

Figures 25 and 26 show, for a period of one year, percent weight gain in representative traveler coupons due to moisture absorption. As can be seen, all tests on coupons conditioned in chamber 1 were tested at $\sim 1\%$ weight gain for laminate 1 and at $\sim 1.1\%$ for laminate 2. This was approximately an equilibrium condition as Figures 23, 24, 25 and 26 display. All testing was completed between 50 $\sqrt{hr}$ and 70 $\sqrt{hr}$. The average total moisture content within the test coupons was approximated as 1.3%.

Figures 25 and 26 show that the coupons were transferred to chamber 2 prior to completion of this first phase of the testing. Note that no significant change in percent weight gain occurred due to the change of chambers. This
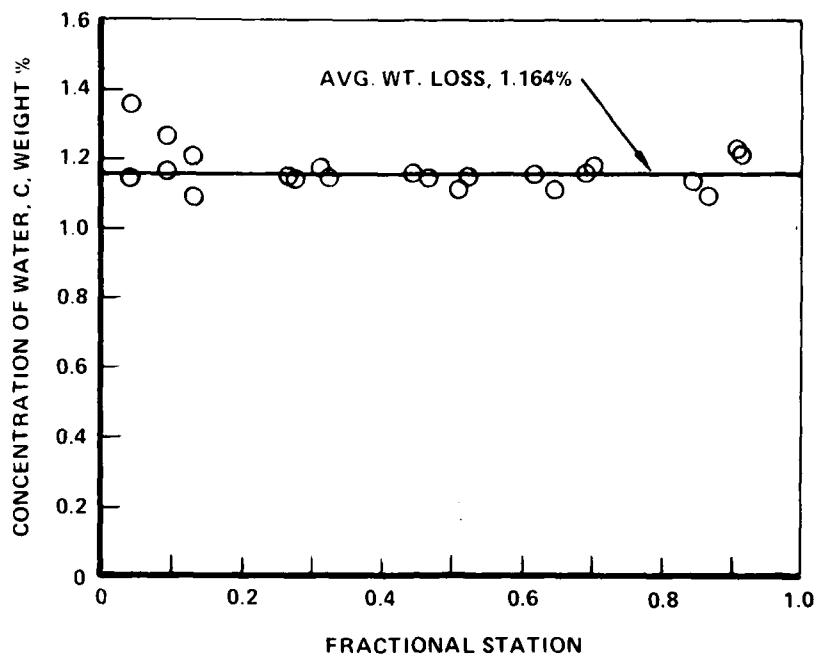
FIGURE 21 MOISTURE DISTRIBUTION IN LAMINATE 1 COUPON ISF1117-D11 AFTER
63 DAYS OF CONDITIONING AT 82.2° C (180°F) AT 90% R.H.
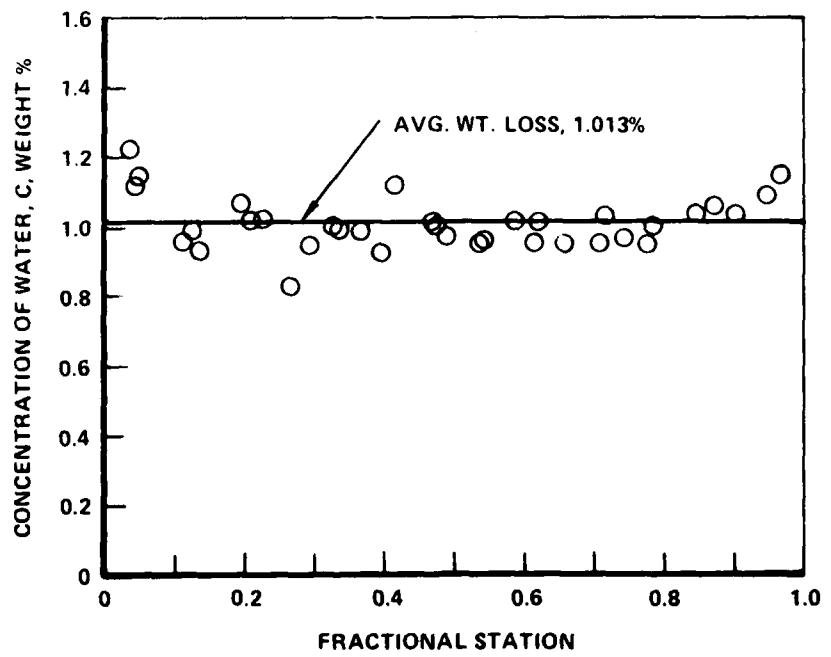
FIGURE 22. MOISTURE DISTRIBUTION IN LAMINATE 2 COUPON ISF1149-A27 AFTER
63 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H.
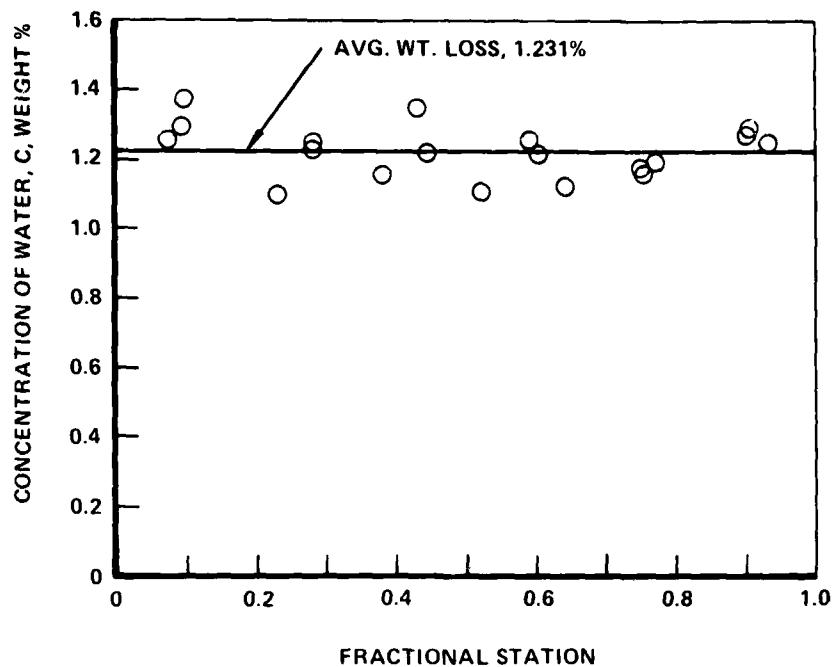
FIGURE 23. MOISTURE DISTRIBUTION IN LAMINATE 1 COUPON ISF1117-D14 AFTER
127 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H.
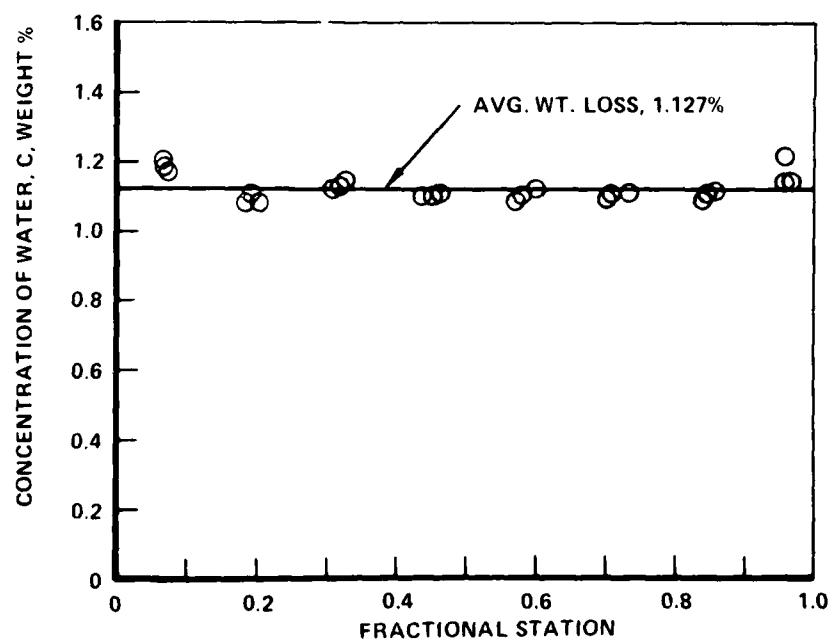
FIGURE 24. MOISTURE DISTRIBUTION IN LAMINATE 2 COUPON ISF1137-A5 AFTER
127 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H.

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TABLE 9

WEIGHT GAIN DUE TO MOISTURE ABSORPTION AT 82.2°C (180°F), 90% R.H. FOR UN-NOTCHED COUPONS

Values given are Moisture Content Increase in Weight Percent

Laminate 1

Days After Placement in Chamber	Coupon ID					
	1SF1117-D11	1SF1117-D31	1SF1117-D2	2SF1117-D17	2SF1117-D20	2SF1117-D2
0	0	0	0	0	0	0
21	.718	.675	.738	.695	.666	.665
42	.742	.692	.737	.711	.691	.690
63	.753	.798	.753	.716	.700	.735
84[a]	-[b]	.771	.805	.758	.791	-
127	-	-[c]	.844[b]	-[c]	.871[b]	1.019
141						1.031
170						.995
200						.947
228						1.166
256						1.252
287						1.341
315						1.345
345						1.413
372						1.197

a - Between 77 and 84 days, the conditioning chamber temperature fell to room temperature and the humidity to ~60% due to equipment malfunction. This resulted in a ~0.03% to 0.06% decrease in weight due to moisture loss.

b - Coupon used for measuring moisture loss during Static Test.

c - Used for Moisture Distribution determination.

TABLE 9 (Continued)

WEIGHT GAIN DUE TO MOISTURE ABSORPTION AT 82.2°C (180°F), 90% R.H. FOR UN-NOTCHED COUPONS

Values given are Moisture Content Increase in Weight Percent

Days After Placement in Chamber	Laminate 2 Coupon ID					
	1SF1149-A27	2SF1133-C26	1SF1137-B20	2SF1133-B8	2SF1137-B2	1SF1149-D9
0	0	0	0	0	0	0
21	.699	.682	.661	.746	.738	.667
42	.809	.808	.789	.832	.817	.788
63	.851	.874	.854	.890	.872	.865
84[a]	- [b]	.964	.937	.955	.945	.936
127	-	- [c]	1.077	1.077[b]	.997[b]	- [c]
141			1.074			
170			1.043			
200			1.020			
228			1.169			
256			1.232			
287			1.319			
315			1.362			
345			1.439			
379			1.310			

a - Between 77 and 84 days, the conditioning chamber temperature fell to room temperature and the humidity to ~60% due to equipment malfunction. This resulted in a ~0.03% to 0.06% decrease in weight due to moisture loss

b - Coupon used for measuring moisture loss during static test

c - Used for Moisture Distribution determination
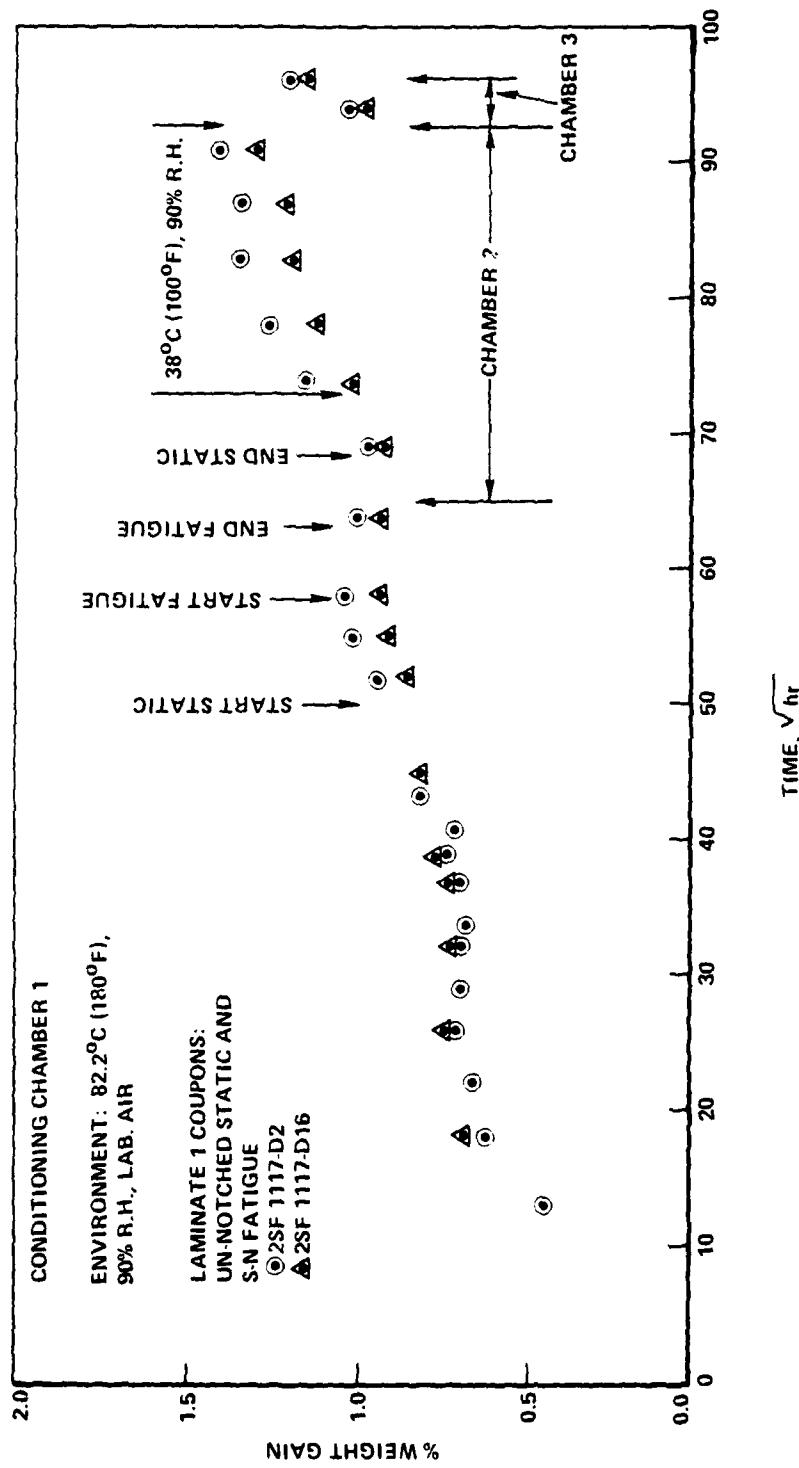
Figure 25. History of Moisture Weight Gain of Representative Laminate 1 Coupons Placed in Conditioning Chamber 1

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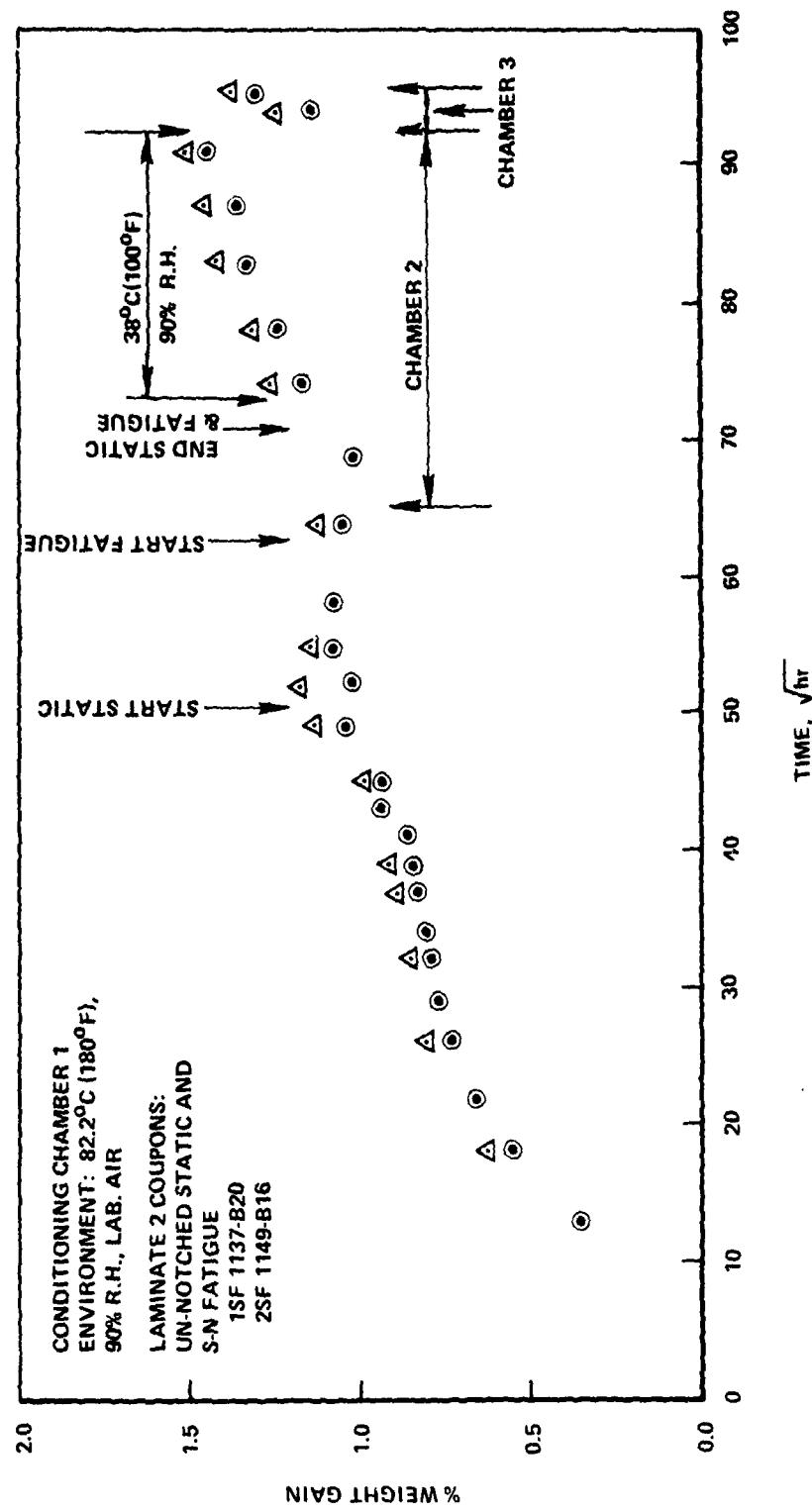
Figure 26. History of Moisture Weight Gain of Representative Laminate 2 Coupons Placed in Conditioning Chamber 1.

65
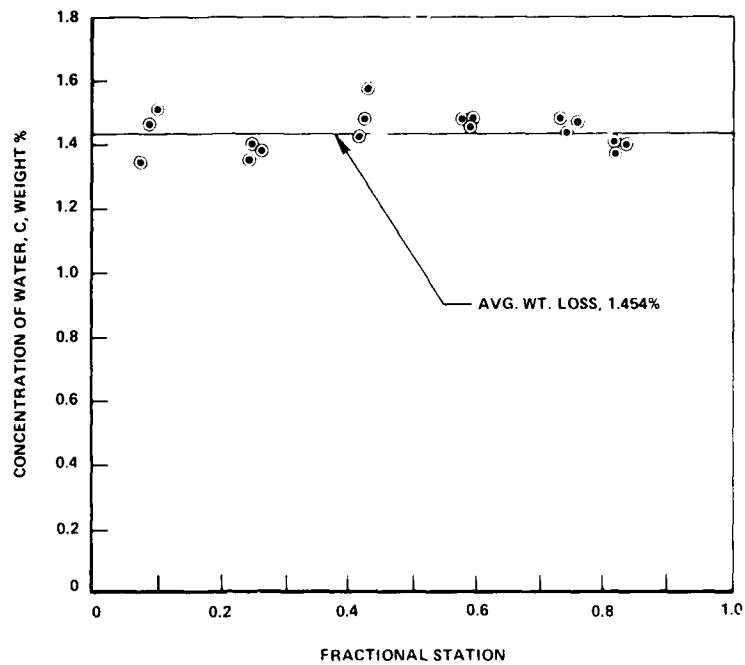
Figure 27. Moisture Distribution in Representative Laminate 1
Coupon 1SF1117-D2 After Conditioning at 82.2°C
(180°F), 90% R.H.
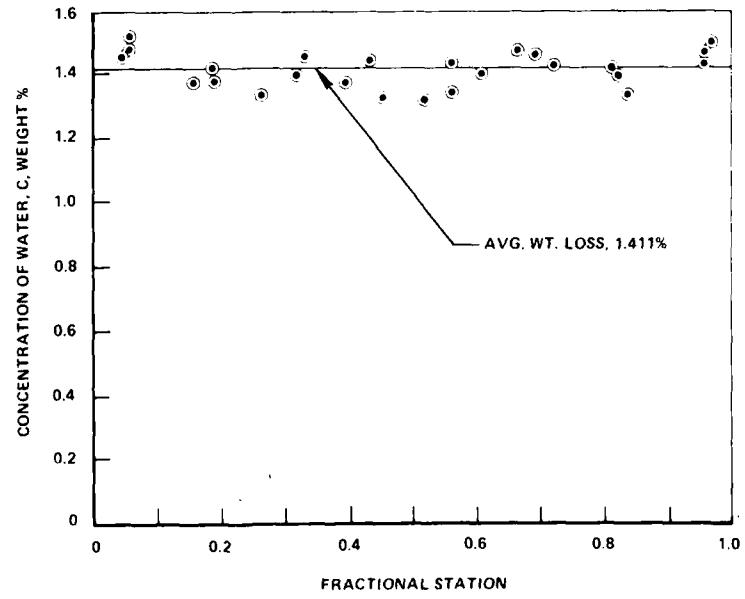
Figure 28. Moisture Distribution in Representative Laminate 2
Coupon 1SF1137-B20 after Conditioning at 82.2°C
(180°F), 90% R.H.
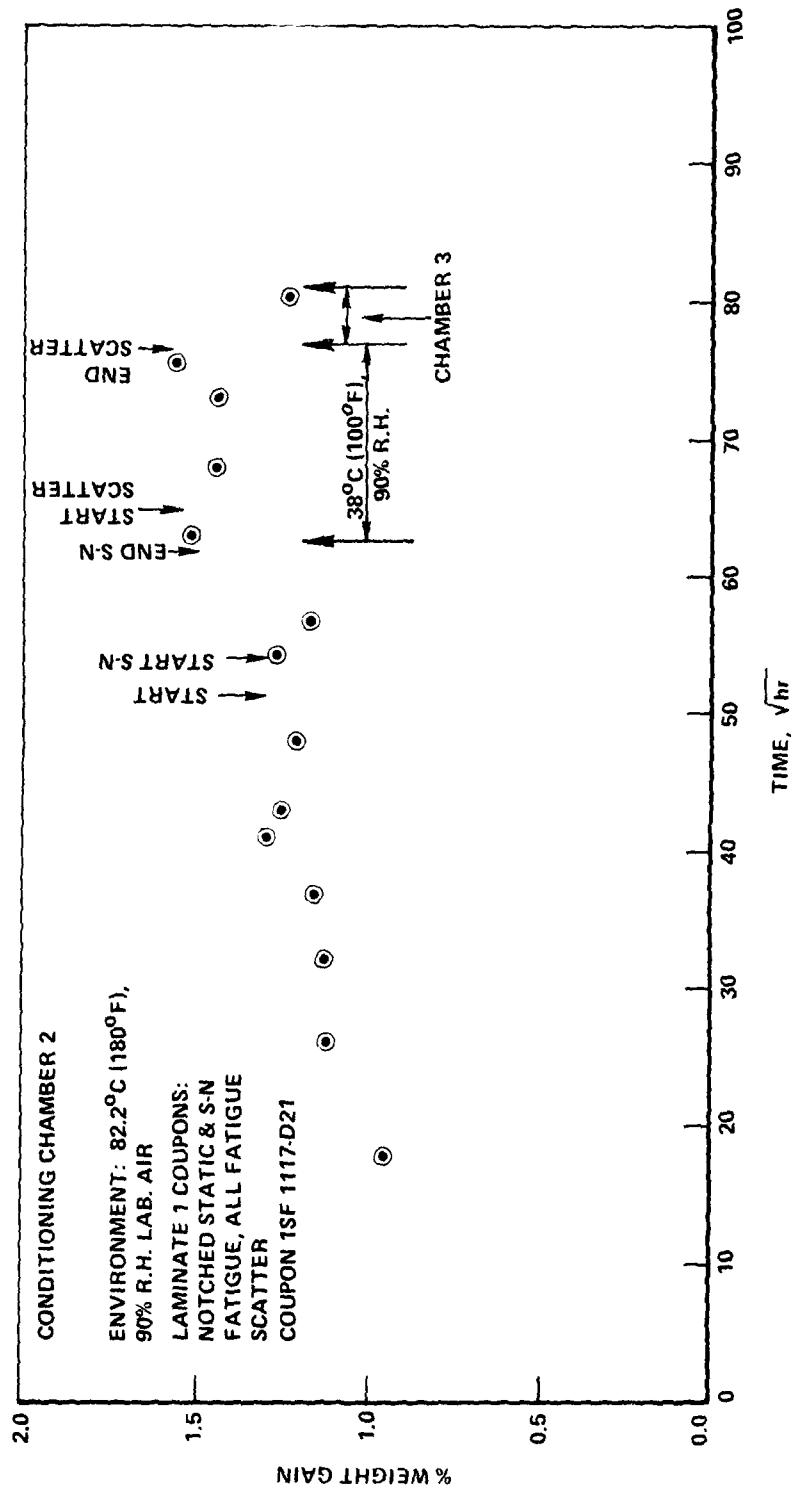
Figure 29. History of Moisture Weight Gain of Representative Laminate 1 Coupons placed in Conditioning Chamber 2
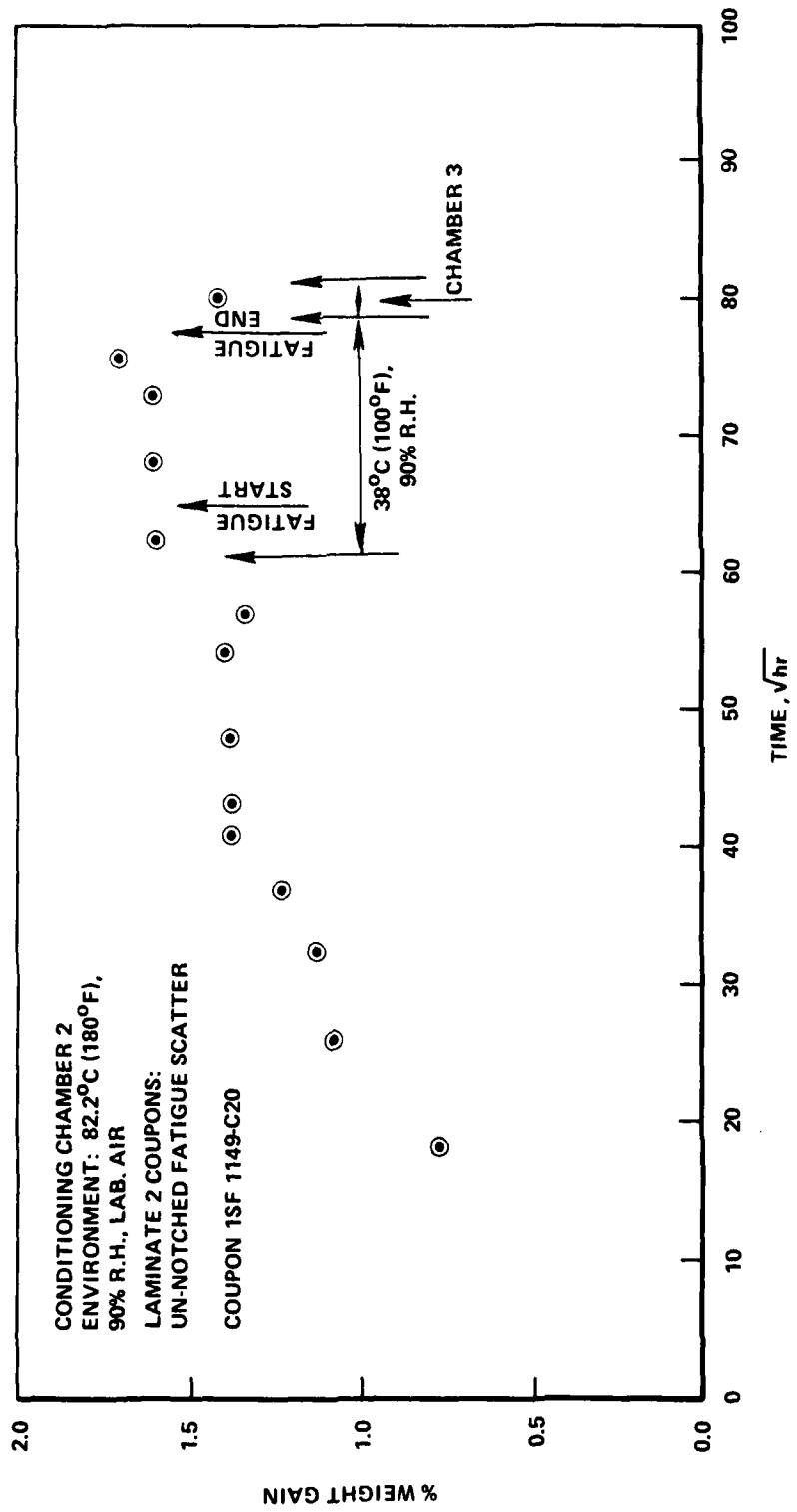
Figure 30. History of Moisture Weight Gain of Representative Laminate 2 Coupons placed in Conditioning Chamber 2.

indicated that the chambers had similar environments as expected. After
testing was complete, the traveler coupons were left in chamber 2. The
chamber temperature was reduced to 38°C (100°F), but the relative humidity
held at 90%. The percent weight gain increased due to this action by approx-
imately 0.4%. This is believed to be due to internal cracking and moisture
absorption due to hydration within the cracks [19, 20]. Subsequently travel-
er coupons were placed in chamber 3 where they did suffer a temporary mois-
ture loss of the same 0.4% when the chamber humidity dropped for two days
due to an equipment malfunction. This result tends to support the sugges-
tion that the original 0.4% increasing was due to cracking and hydration.
The coupons remained in essentially an equilibrium moisture content level
as shown by the representative coupons displayed in Figures 27 and 28 which
were removed after 95 $\sqrt{hr}$. of conditioning.

Mechanical tests conducted using coupons conditioned in chamber 2 were:
laminate 1 notched static, notched stress-life fatigue, and all fatigue
scatter; laminate 2 un-notched fatigue scatter. Figures 29 and 30 show weight
gain due to moisture absorption in traveler coupons representative of the
six used for each group of test specimens. Similar to coupons conditioned
in chamber 1, testing was conducted on these coupons between 55 $\sqrt{hr}$. and
75 $\sqrt{hr}$. Laminate 1 notched coupons used in static tension and S-N fatigue
were tested between 55 $\sqrt{hr}$. and 62 $\sqrt{hr}$. once had an average moisture con-
tent of approximately 1.5% after adding the initial moisture content to that
shown in Figure 29. However, the notched and un-notched coupons of both
laminates used for determining fatigue scatter had an average moisture content
of approximately 1.8% as determined by adding the initial moisture content to
that shown in Figures 29 and 30. Thus, un-notched coupons used for deter-
mining static strength distributions and initial S-N fatigue life curves had
an average moisture content of approximately 1.3% as contrasted with the
1.8% moisture content of those used for the fatigue scatter study. This un-
expected difference allowed for qualitative determination of the effect of
moisture content on fatigue life.

The higher moisture content appears to have been due to the same cracking/hydration problem described previously as a result of allowing the oven temperature to decrease while maintaining high humidity. The oven temperature was reduced in the first place to prevent excessive conditioning and damage to the coupons. Instead, the opposite may have occurred. Despite the temporary perturbation in the traveler coupon moisture content while in chambers 2 and 3 (see Figures 29 and 30), final moisture content that was still essentially equilibrated at the end of 75 $\sqrt{hr}$.
see Figure 31 and 32.

Why the moisture content of traveler coupons placed initially in chamber 2 was $\sim$ 0.1% higher after 50 $\sqrt{hr}$. of conditioning than those initially placed in chamber 1 is not known. Likewise, the reason for the initial more rapid rate of moisture rise is not clear. These differences would normally be expected to be due to differences in the environmental conditions within chambers 1 and 2. If this is the reason the difference was small because traveler coupons from chamber 1 did not gain weight when placed in chamber 2.

Residual strength testing was conducted using coupons conditioned in chamber 3. Typical weight gain records are shown in Figures 33 and 34. As with previous coupons, testing was conducted after 50 $\sqrt{hr}$. of conditioning and before 75 $\sqrt{hr}$. This resulted in a total moisture content in these coupons of $\sim$ 1.3%. The rate of weight increase and equilibrium weight gain in these coupons was essentially the same as those placed in chamber 1. The small perturbation in moisture content which occurred due to chamber malfunction is apparent in Figures 33 and 34. The moisture distributions of two representative traveler coupons are shown in Figures 35 and 36 and show the nearly equilibrium moisture contents found after removal from the chamber at 65 $\sqrt{hr}$.

Group 4: Coupons used for determining weight loss and moisture distribution changes which occurred during static testing.

Because of the experimental difficulties of statically testing coupons conditioned at 82.2°C (180°F) and at 90% R.H. in a 82.2°C (180°F), 90% R.H.
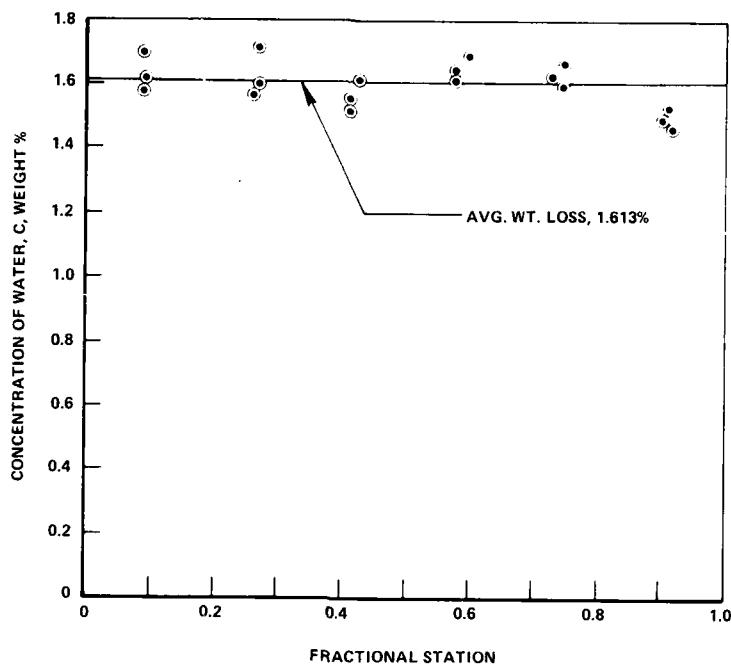
Figure 31.   Moisture Distribution in Representative Laminate 1
Coupon 1SF1117-D21 after Conditioning at 82.2°C
(180°F), 90% R.H.
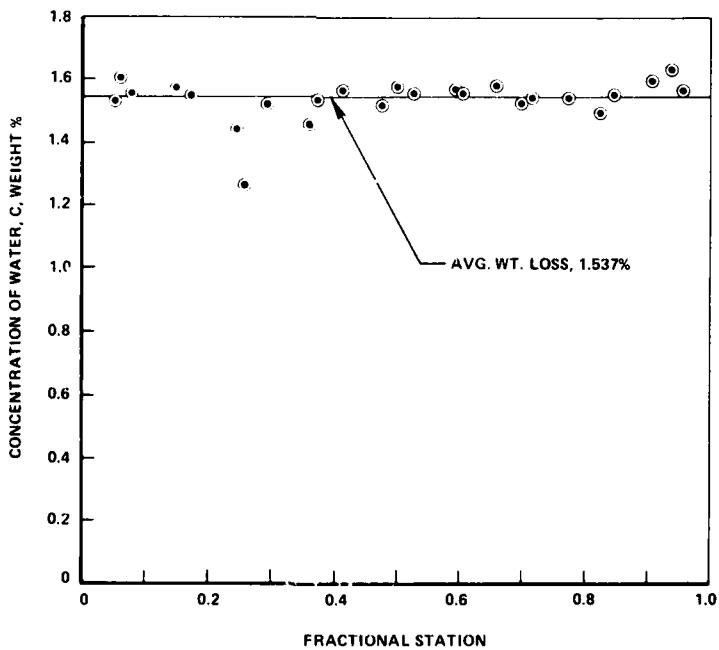
Figure 32.   Moisture Distribution in Representative Laminate 2
Coupon 1SF1149-C20 after Conditioning at 82.2°C
(180°F), 90% R.H.

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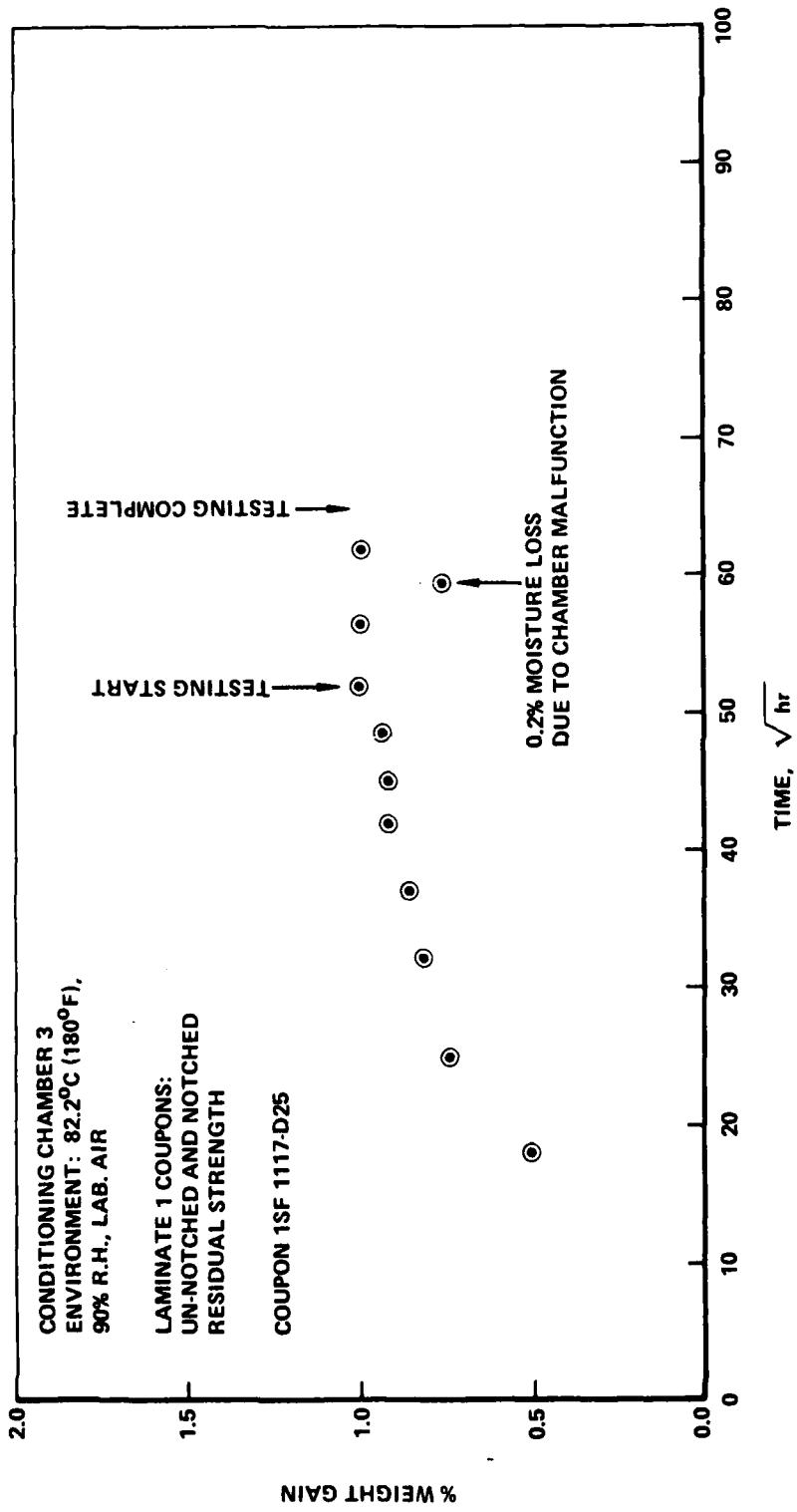
Figure 33. History of Moisture Weight Gain of Representative Laminate 1 Coupons placed in Conditioning Chamber 3
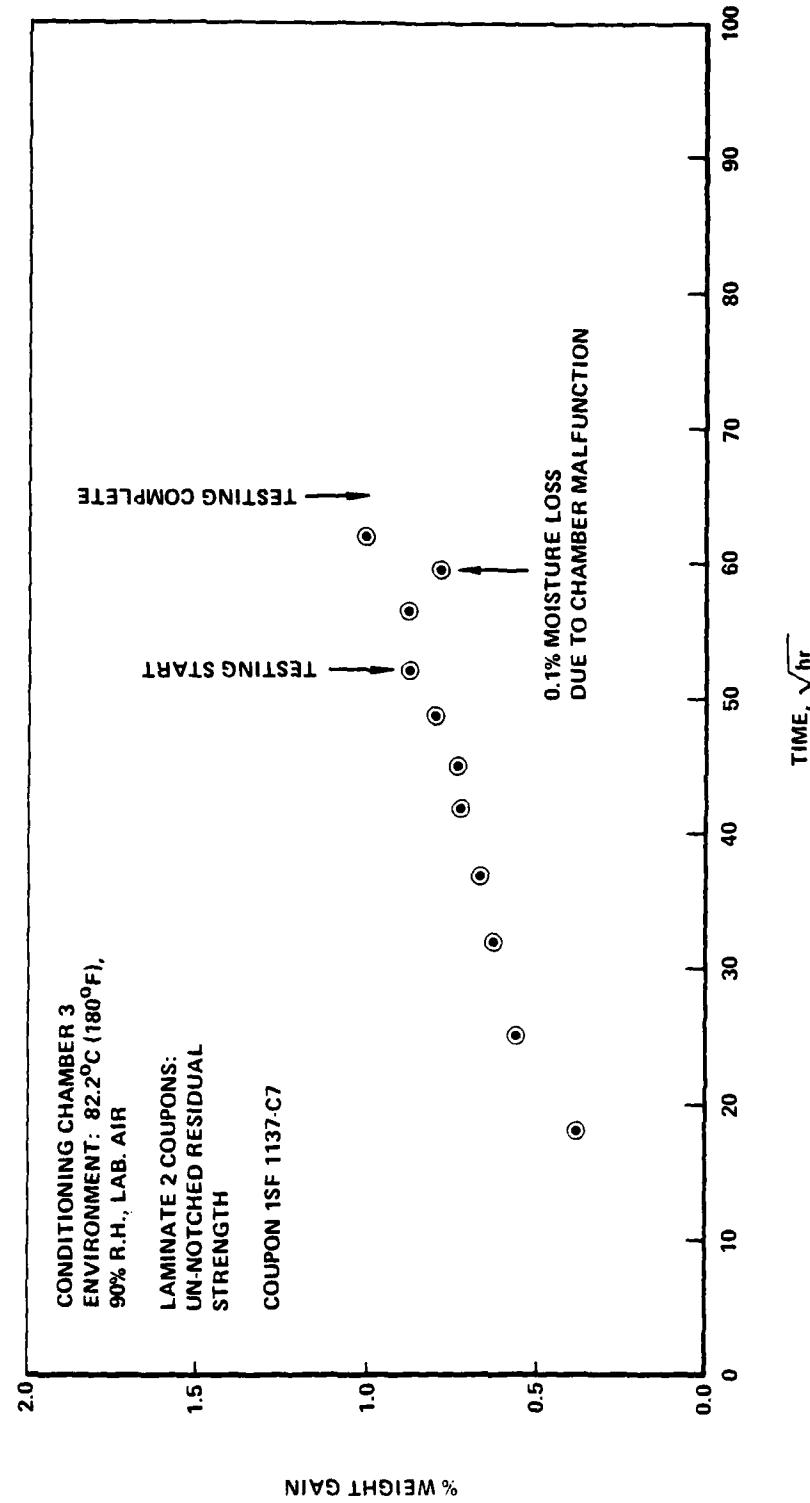
Figure 34. History of Moisture Weight Gain of Representative Laminate 2 Coupons placed in Conditioning Chamber 3

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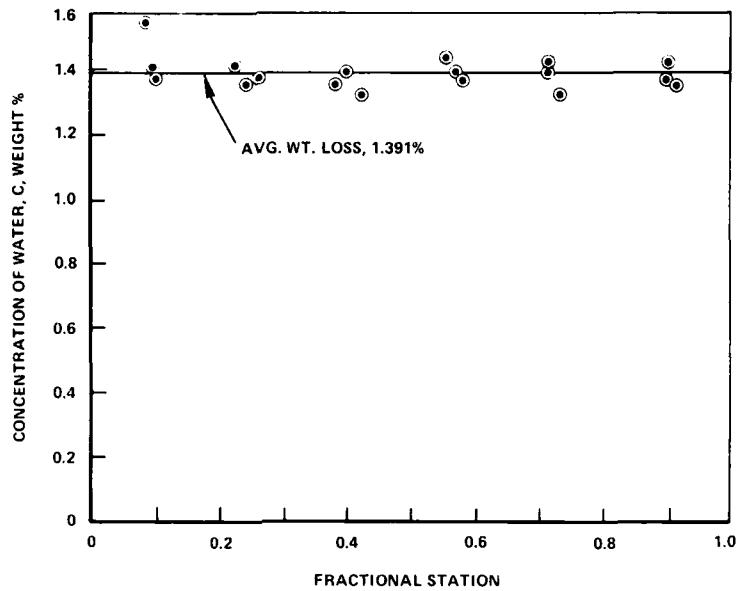
Figure 35. Moisture Distribution in Representative Laminate 1 Coupon 1SF1117-D25 after Conditioning at 82.2°C (180°F), 90% R.H.
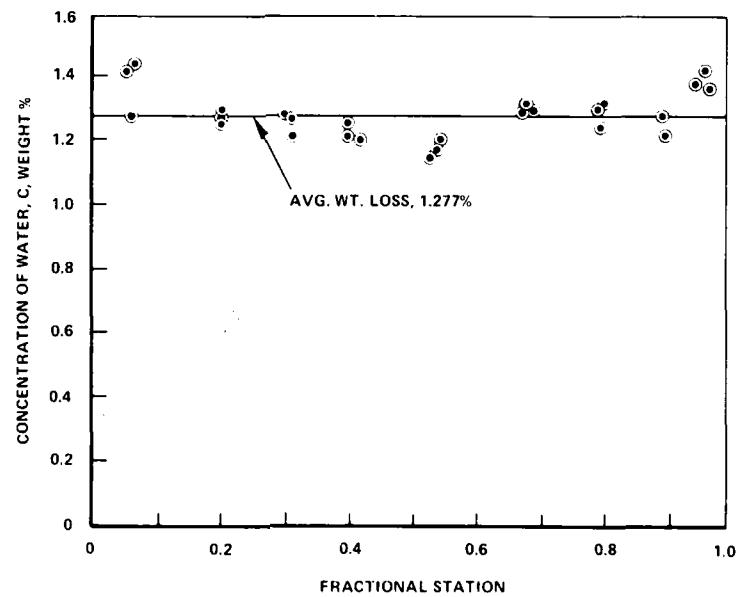
Figure 36. Moisture Distribution in Representative Laminate 2 Coupon 1SF1137-C7 after Conditioning at 82.2°C (180°F), 90% R.H.

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environment, all of the high temperature static tests were conducted without humidity to the laboratory air environment. Therefore, an investigation was conducted as to the effect on the moisture gain and distribution due to exposure of the specimens to the 82.2°C (180°F), laboratory air environment. Figures 37 to 42 show the experimentally measured moisture distribution and average weight loss/gain for laminate 1 and 2 coupons which went through a typical static test thermal cycle.

Figures 37 and 38 show the results for a 5-minute soak at 82.2°C (180°F) and a 3-minute static test after a 94-day conditioning exposure. Similarly, Figures 39 to 42 show the results for a 2-minute soak at temperature and a 3-minute static test. These results show that the time at temperature without high humidity essentially reduced the outside ply moisture by ~ 0.1 to 0.2% without affecting the interior plies significantly. Therefore, the static tests were conducted with a 2-minute soak, sufficient to obtain temperature equilibrium within the coupons, followed by a 3 to 4-minute test time. Table 10 shows typical recorded moisture losses which occurred during the static testing. Except for two coupons, all weight losses which occurred during the static tests were less than 0.075%. These two values were higher due to the 8 min. test time.

Summary

The initial average moisture content within the traveler coupons ranged from 0.1% to 0.6%. This average value increased by less than 0.2% from the beginning of room temperature testing to the end. Therefore, the room temperature data can be cross compared with confidence although a small difference due to the increased moisture must be accounted for as was shown previously [1].

Conditioning at 82.2°C (180°F), 90% R.H. for 90 days led to an essentially equilibrium moisture content of ~ 1.3% within the traveler coupons. Subsequently, moisture content increased to ~ 1.7% for coupons used for fatigue scatter studies. The first level is compatible with previously reported work [21] while the second appears typical of a second equilibrium plateau
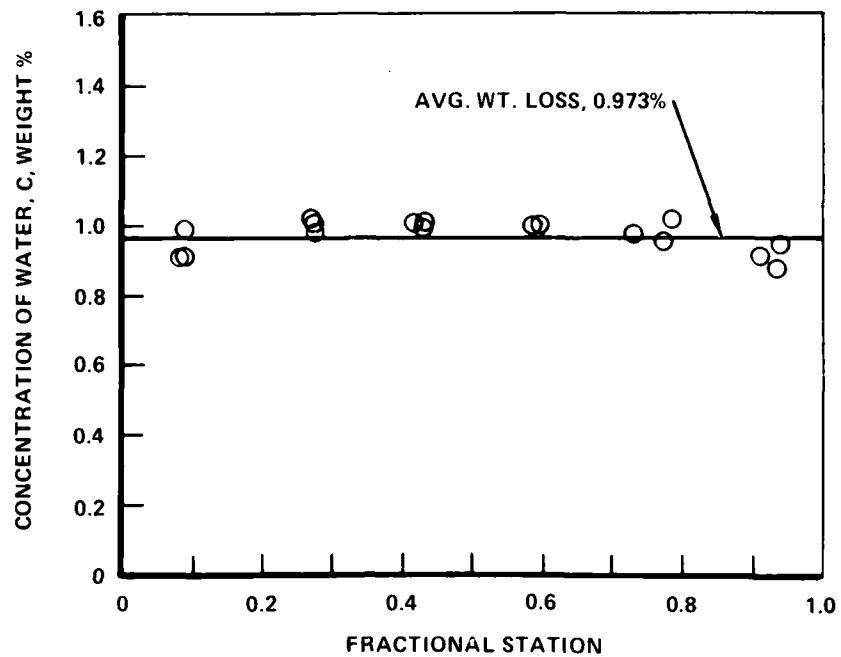
FIGURE 37. MOISTURE DISTRIBUTION IN LAMINATE 1 COUPON 1SF1117-D1 AFTER 94 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H. AND EXPOSED 8 MIN. AT 82.2°C (180°F) IN LABORATORY AIR DURING COMPRESSION TEST
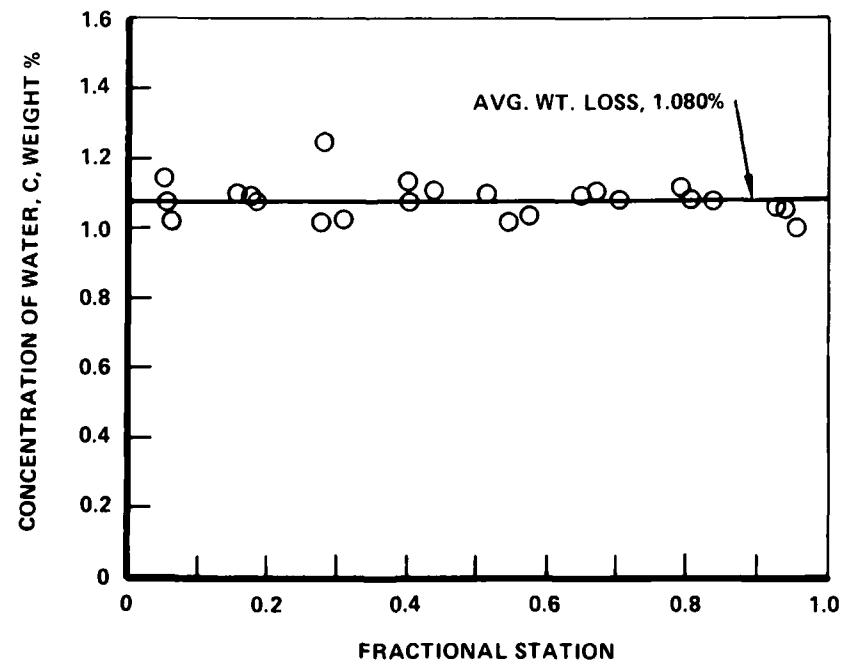
FIGURE 38. MOISTURE DISTRIBUTION IN LAMINATE 2 COUPON 2SF1133-C26 AFTER 94 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H. AND EXPOSED 8 MIN. AT 82.2°C (180°F) IN LABORATORY AIR DURING COMPRESSION TEST
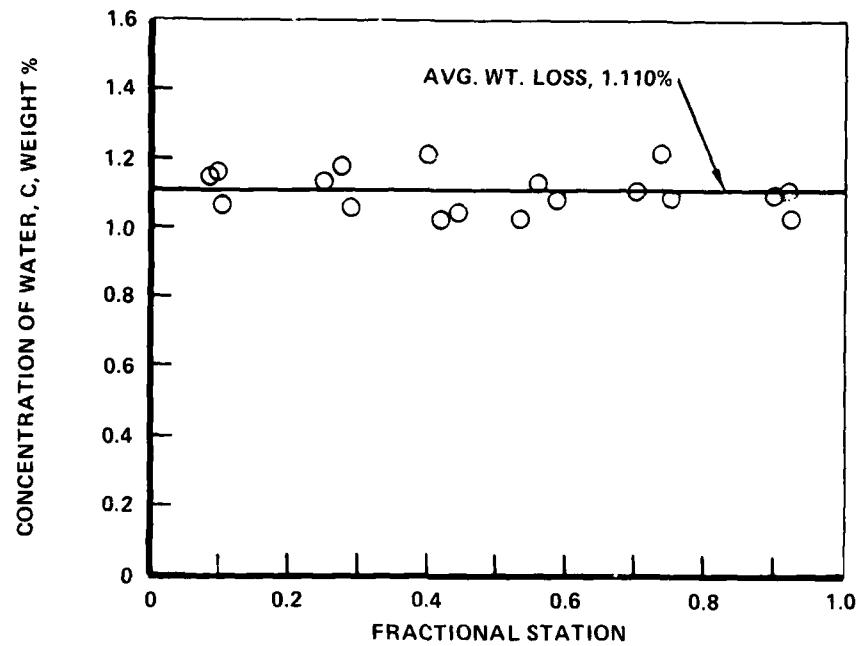
FIGURE 39. MOISTURE DISTRIBUTION IN LAMINATE 1 COUPON 2SF1117-D2 AFTER
127 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H. AND
EXPOSED 5 MIN. AT 82.2°C (180°F) IN LABORATORY AIR DURING
TENSION TEST
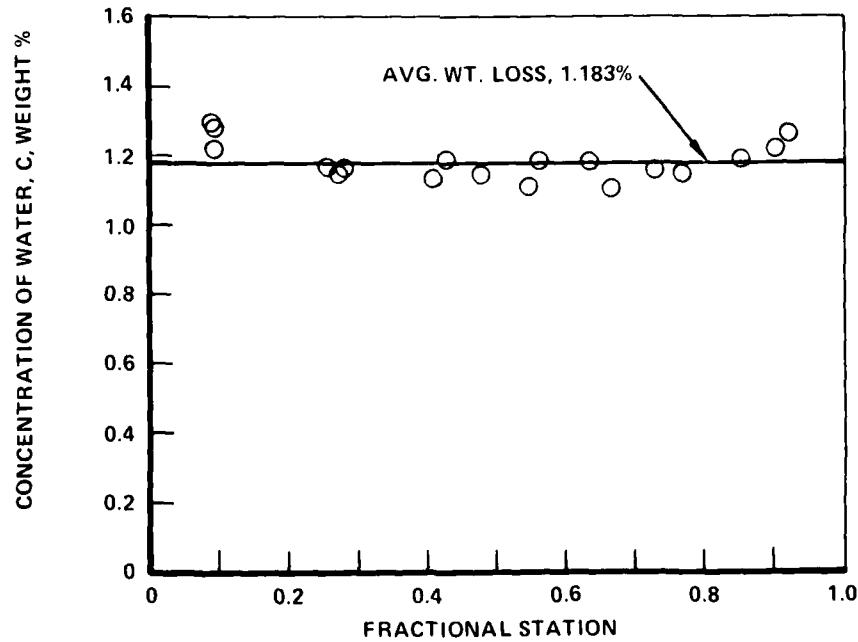
FIGURE 40. MOISTURE DISTRIBUTION IN LAMINATE 1 COUPON 2SF1117-D20 AFTER
127 DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H. AND EXPOSED
5 MIN. AT 82.2°C (180°F) IN LABORATORY AIR WHILE IN COMPRESSION
GUIDE

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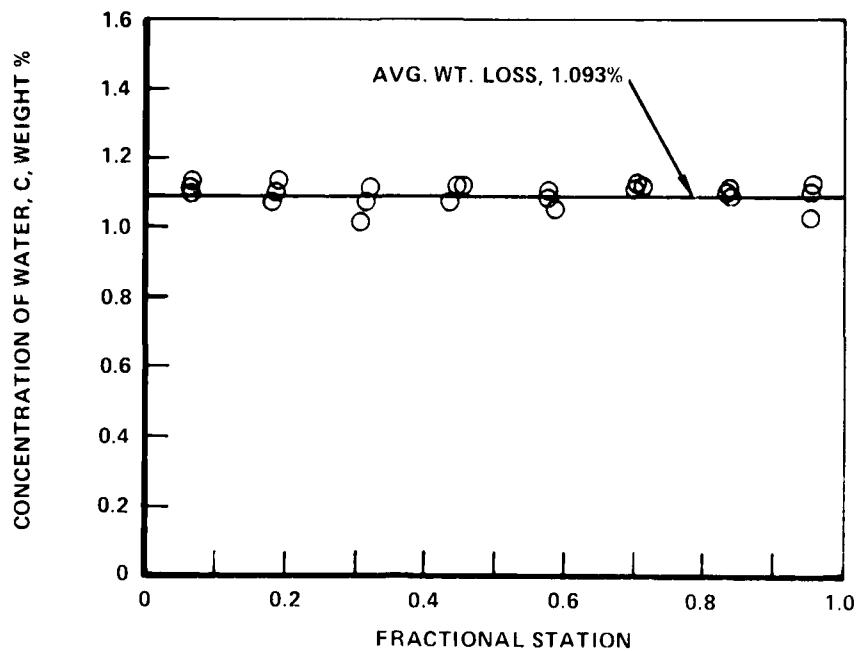
FIGURE 41   MOISTURE DISTRIBUTION IN LAMINATE 2 COUPON 2SF 1133-B8 AFTER 127
DAYS OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H AND EXPOSED 5 MIN.
AT 82.2°C (180°F) IN LABORATORY AIR DURING TENSION TEST
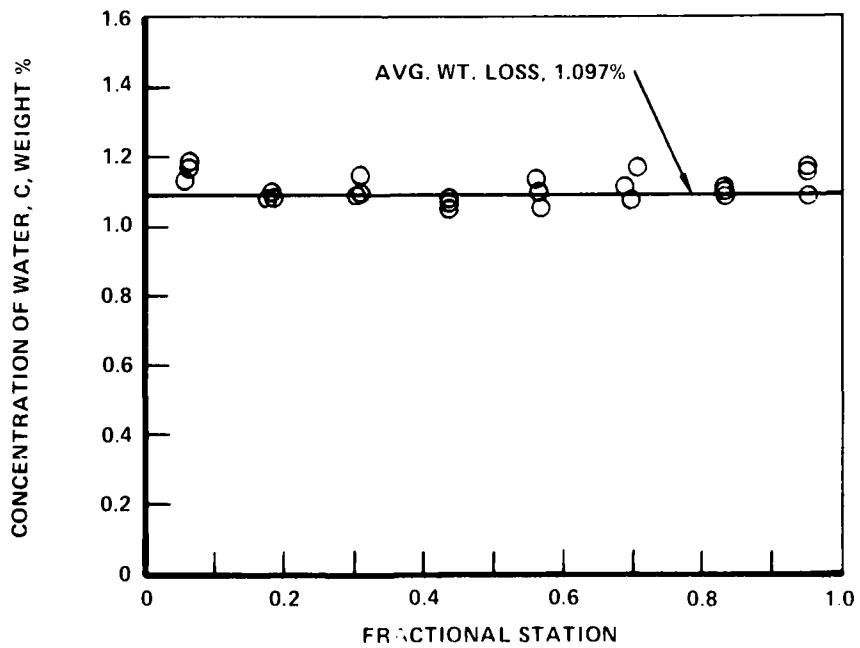
FIGURE 42.   MOISTURE DISTRIBUTION IN LAMINATE 2 COUPON 2SF 1137-B2 AFTER 127 DAYS
OF CONDITIONING AT 82.2°C (180°F) AT 90% R.H. AND EXPOSED 5 MIN. AT
82.2°C (180°F) IN LABORATORY AIR DURING COMPRESSION TEST

TABLE 10

MOISTURE LOSSES WHICH OCCURRED DURING STATIC TESTING

Laminate	Traveler Coupon ID	No. of Days of Conditioning Prior to Test	Test Type with which Coupon was Placed	Time at 32°C (150°F)	Weight Loss, %
1	1SF1117-D2	127	T [a]	2	.034
	1SF1117-D31	94	C	5	.071
	2SF1117-D5	131	T	5	.020
	2SF1117-D17	101	T	8	.195
	2SF1117-D20	127	C [b]	5	.020
2	2SF1133-B8	127	T	5	.024
	2SF1133-C26	94	C	8	.114
	2SF1133-D18	101	T	5	.008
	2SF1137-B2	127	C	5	.010
	2SF1137-B24	93	C	5	.069
	1SF1149-D9	101	T	5	.040

a - T - Static Tension Test, C - Static Compression Test

b - Coupon was placed between full-fixity compression guide

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reportedly [19, 20] due to cracking and moisture hydration. Testing was conducted on coupons with the two different moisture levels. The tests conducted and corresponding moisture levels are summarized in Table II. The moisture levels obtained resulted in a consistent data set for static, S-N fatigue, and residual strength for both laminates. The fatigue scatter data was obtained at a higher level which resulted in data which allowed comparison of the effect of moisture and temperature at three test conditions: 22°C (72°F) ~ 0.4% moisture; 82.2°C (180°F), ~ 1.3% moisture; 82.2°C (180°F), ~ 1.7% moisture.

TABLE 11

PERCENT MOISTURE CONTENT WITHIN COUPONS TESTED UNDER
DIFFERENT CONDITIONS AT 82.2°C (180°F), 90% R.H.

Laminate	Test Type	Approximate Average Moisture Content	
		Un-Notched	Notched
	Static	1.3	1.5
	Stress-Life Fatigue	1.3	1.5
1	Fatigue Scatter	1.7	1.7
	Residual Strength	1.3	1.5
	Static	1.3	-
	Stress-Life Fatigue	1.3	-
2	Fatigue Scatter	1.7	-
	Residual Strength	1.3	-

SECTION V

STATIC TENSION AND COMPRESSION RESULTS

5.1   STATIC TENSION TEST RESULTS, ROOM TEMPERATURE

Un-notched

The static tension tests were conducted not only to determine the panel mechanical properties, but also to ascertain to a limited extent, panel to panel variations. Therefore, five un-notched coupons were tested from each panel at room temperature in laboratory air.

For both laminates all un-notched failures were brittle-like without any discernable plastic-like flow at the end of the stress-strain curve. Stress-strain curves of laminate 1 tensile coupons exhibited an initial straight, apparently elastic portion with an apparent modulus of elasticity designated as E_{1a}. This straight portion was followed by a short, gradual, change to a second, inelastic, straight curve to failure with an apparent modulus designated E_{1b}. In contrast, stress-strain curves of laminate 2 coupons exhibited a nearly linear behavior to failure with an apparent modulus designated E_2. The stress-strain curves for both laminates were similar to those previously observed [1]. All tensile failures of laminate 1 coupons were within the gage length. Those which failed near the end did not differ in their failure strengths from those of the majority of coupons which failed near the center. Most of the laminate 2 coupons failed near the end of the gage length. Tensile strengths of those failed closer to the center were the same as those which failed near the end of the gage length. In general, failed laminate 1 static tension coupons were observed to have more extensive delamination than laminate 2 coupons.

Typical static tension failures of un-notched laminate 1 coupons are shown in Figure 43. Only minor amounts of delamination occurred which was essentially confined to the fracture region. Matrix failures occurred in the 90° and
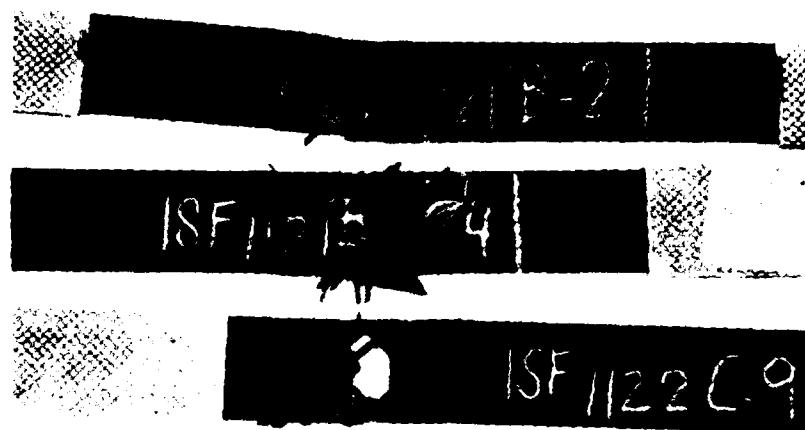
a. Side View: Coupons 2SF1121-B2, 1SF1121-B24, 1SF1122-C9
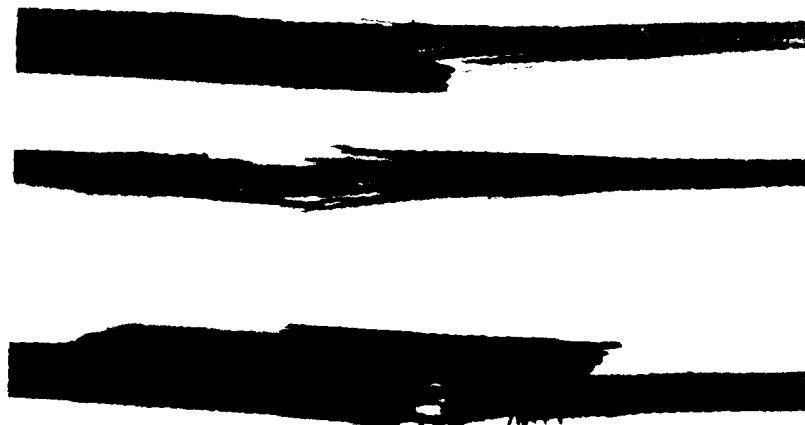
b. Edge View: Coupons 2SF1121-B2, 1SF1122-C9, 1SF1121-B24

Figure 43.   Representative Un-notched Laminate 1 Coupons which Failed
               in Static Tension at Room Temperature in Laboratory Air

±45° ply layers while the fibers in the 0° plies fractured. Fibers in the outer 0° plies often failed along a ±45° direction indicating a strong influence of the ±45° plies on the fracture process. Multiple failure locations sometimes occurred.

Laminate 2 coupons which failed under static tension loading typically exhibited one localized fracture region dominated by 0° fiber breaks, ±45° ply matrix failures and extensive delaminations over a large portion of the coupon, see Figure 44. Occasionally, failure regions were dominated by fracture of the 0° fibers along a line ±45° to the load line direction.

Room temperature static tension tests were conducted on 55 un-notched laminate 1 coupons and on 25 un-notched laminate 2 coupons. The data is tabulated in Appendix B, Tables B1 to B4 including listings of panel to panel variations. Tables 12 and 13 contain summaries and comparisons of the tension test data. This un-notched room temperature static tension data is compared to the previous data of Reference 1 in Table 14. The panel to panel variation in laminate 1 average static tensile properties had a coefficient of variation of 2.2%. This is similar to the best metal variations due to heats of metal from the same ingot of material. A similar variation was found for the laminate 2 material.

Table 12, which compares the two sets of data using all data points, shows that the two laminates have quite similar coefficients of variation for each of their properties. The Weibull parameters given in Table 13 also show that the difference in statistical properties of the two layups lies primarily in their characteristic strengths. Table 14 shows a comparison between the panels reported in Reference 1 and those tested for the present contract. The increase in average ultimate strength properties can be attributed to the increase in fiber strength, reflected mainly in the increased strains to failure, and the increased fiber volumn. The slight loss of fiber modulus (<2%) coupled with increased fiber volumn resulted in essentially unchanged laminate moduli.

139 108R
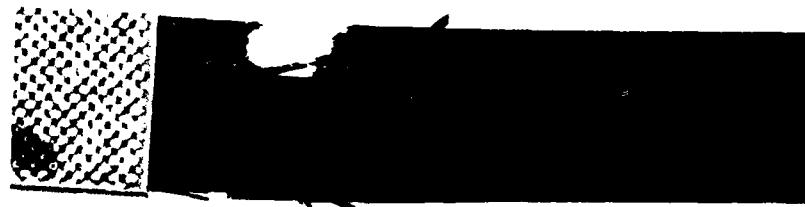
a. Side View: Coupons 2SF1137-A2, 2SF1137-A19
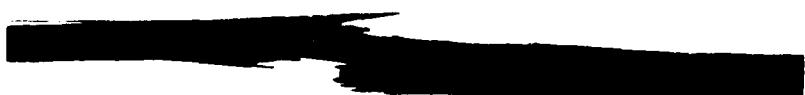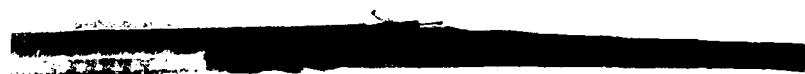
139 051R

b. Edge View: Coupons 2SF1137-A2, 2SF1137-A19

Figure 44. Representative Laminate 2 Coupons which Failed in Static Tension at Room Temperature in Laboratory Air

TABLE 12

SUMMARY OF UN-NOTCHED STATIC TENSION TEST RESULTS AT ROOM TEMPERATURE

		Average Ultimate Stress σ_{ult} MPa (ksi)	Average Ultimate Strain ϵ_{ult}, in./in. in 2 in.	Average Initial Apparent Modulus of Elasticity E_A, GPa (psi x 10^6)
Laminate 1	Average	56.7 (82.3)	.0113	53.3 (7.73)
	Std. Deviation	28.5 (4.13)	.00046	1.94 (0.281)
	Coeff. of Var. %		4.1	
Laminate 2	Average	1110 (161.0)	.0105	105.5 (15.3)
	Std. Deviation	58.1 (8.42)	.00046	2.62 (0.38)
	Coeff. of Var. %		4.4	

TABLE 13

SUMMARY OF UN-NOTCHED STATIC TENSION TEST PARAMETERS AT ROOM TEMPERATURE

	Number of Weibull Parameters	Weibull Coefficients			Coefficient, R
		k	θ	ν	
Laminate 1	3[a]	24.707	-0.2784	83.983	0.99844
	2[a]	23.570	0	84.394	0.99818
	2[b]	22.906	0	84.194	0.98485
Laminate 2	3[a]	21.830	-0.1421	164.079	0.99950
	2[a]	21.792	0	164.211	0.99950
	2[b]	20.954	0	164.814	0.98965

$$P(x) = \exp\left[-\left(\frac{x-\theta}{\nu-\theta}\right)^k\right]$$

a - Weibull Coefficients obtained by iteration on R in single logarithmic space

b - Weibull Coefficients obtained directly by linear least square analysis in double logarithmic space

TABLE 14

COMPARISON OF ROOM TEMPERATURE, UN-NOTCHED, STATIC TENSION PROPERTIES AT ROOM TEMPERATURE: MANUFACTURED FROM DIFFERENT BATCHES

Lockheed Batch Code	Laminate 1		Laminate 2	
	NL^a	SP^b	NL^a	SP^b
Average Ultimate Stress, σ_{max}, MPa (ksi)	477 (69.2)^c	567 (82.3)	977 (141.7)	1110 (161.0)
	23.4 (3.39)	28.5 (4.13)	64.0 (9.29)	58.0 (8.42)
	4.9%	5.0%	6.56%	5.2%
Avg. Strain to Failure, ε mm/mm in 50.8 mm	0.0096	0.0113	0.0092	0.0105
	0.00059	0.00046	0.00087	0.00046
	6.2%	4.1%	9.4%	4.5%
Avg. Initial Apparent Modulus of Elasticity, E_A, GPa (psi x 10^6)	52.7 (7.64)	53.3 (7.73)	106 (15.4)	105.5 (15.3)
	2.14 (0.31)	1.93 (0.28)	7.17 (1.04)	2.62 (0.38)
	4.0%	3.6%	6.7%	2.5%

a - Material used in Contract F33615-75-C-5118, data reported in AFML-TR-76-241

b - Material used in present Contract, F33615-77-C-5045

c - Avg., Std. Dev., Coeff. of Var. in each Table entry

The laminate 1 static tension data summarized in Tables 12 to 14 contains data from different populations of coupons other than that due to panel to panel variations. The reason for separation of the laminate 1 static tension data into different populations is due to the fact that many coupons contained a line discontinuity within them. This line discontinuity was caused by the adjoining of separate sections of prepreg tape during the manufacturing of the panels.

In the particular layup used for the quasi-isotropic panels, three 0° line discontinuities were at the same two locations within the panel while individual 0° line discontinuities were at three other locations. There were three 90° direction line discontinuities regions within the panels each consisting of four coincident lines of adjoining tape edges. However, the coupons within each panel were laid out in such a way that these 90° line discontinuities were well within the coupon tab regions or within the central region of the panel not used for coupons. Within each panel, the ± 45° plies had four regions of line discontinuity of four plies each. The tape (line discontinuity) layout within each panel is shown in Figures A1 and A2 of Appendix A. Two panels (1 and 2SF 1117) were mistakenly machined with the central region, used for panel analysis, taken from the bottom of the panel instead of the top. This forced the bottom 90° line discontinuity to be within the D subpanel gage length on these two panels. Because of the large effect of this 90° line discontinuity on the matrix strength, the D subpanel coupons from these two panels were not used for any further testing.

The effect of line discontinuity on the static strength of the laminate 1, quasi-isotropic panels used in this investigation is shown in Table 15 with details listed in Appendix Table B5. The tensile strength of all coupons which contained a three 0° line discontinuity region was on the lower range of strength; see Table 15. The 90° line discontinuity had a greater effect than the 0°. This was due to the fact that at a 90° discontinuity, 0° fibers can sag into the gap formed by the 90° line discontinuity region. No attempt was made to study the effect of the ±45° line discontinuities since almost all coupons had such a discontinuity.

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The coefficient of variation significantly decreased and the shape parameter k significantly increased by removing from the population those coupons which contained line discontinuities, see Table 15.

A hypothesis is offered to explain the reason why the line discontinuity should drastically lower the static strength. Prepreg tape is manufactured using multiple tows of fibers drawn from spools while under tension. The tows on the outer edge of tape have a significantly different tension than those within the tape apparently due to cutting of the tape. This is often evident in a puckering of the tape edge when unrolled. During manufacturing, tape edges are butted together and smoothed. This manufacturing process produces a line discontinuity within a panel along the tape edge. Most likely the smoothing process damages some fibers and the curing process produces matrix cracking along the line discontinuity. Therefore, the line discontinuity results in a preferential, and predamaged region which causes a lowering in static strength. Although an effect of the line discontinuity would be expected to occur in the $0°$, $45°$ or $90°$ direction, the largest effect would normally be expected to be due to the $0°$ direction. However, in this particular case the worst effect was found for the $90°$ direction for the reasons previously discussed.

The effect of a line discontinuity on the laminate 2, un-notched static strength properties was similarly investigated. Table 16 shows the results of the investigation which is listed in Appendix Table B6. The presence of the $0°$ line discontinuity affected the strength, but possibly not as significantly as for laminate 1 coupons.

Notched

Details of the notched laminate 1 static tension properties obtained in room temperature, laboratory air, are listed in Appendix B Table B7. Results are summarized and compared to the unnotched data in Table 17. The effect of the hole appears to be well predicted by the "Point Stress Criteria" of Nuismer and Whitney [22]. Typical laminate 1 static tension fractures of

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TABLE 15

EFFECT OF LINE DISCONTINUITY ON TENSILE STRENGTH OF UN-NOTCHED LAMINATE 1 COUPONS AT

ROOM TEMPERATURE IN LABORATORY AIR

	Average Ultimate Strength, σ_{max} MPa (ksi)		Standard Deviation MPa (ksi)		Coefficient of Variation %	Weibull Parameters			Correlation Coefficient R
						k	e	v	
Complete Data Set (Sample Size = 72)	563	(81.7)	34.1	(4.94)	6.04	20.30	-0.271	83.81	0.9990
Coupons W/O 90° Line Discontinuity (Sample Size= 69)	567	(82.2)	28.2	(4.09)	4.98	24.12	-0.319	84.03	0.9982
Coupons W/O 0° and 90° Line Discontinuity (Sample Size= 56)	576	(83.6)	21.9	(3.18)	3.80	33.88	-0.640	84.91	0.9964

TABLE 16

EFFECT OF LINE DISCONTINUITY ON TENSILE STRENGTH OF UN-NOTCHED LAMINATE 2 COUPONS

AT ROOM TEMPERATURE IN LABORATORY AIR

	Average Ultimate Strength, σ_{max}		Standard Deviation, σ		Coefficient of Variation %	Weibull Parameters			Correlation Coefficient, R
	MPa	(ksi)	MPa	(ksi)		k	e	v	
Complete Data Set (Sample Size= 25)	1110	(161.0)	58.1	(8.42)	5.23	21.8	-0.142	164.1	0.9995
Coupons W/O Line Discontinuity (Sample Size= 20)	1124	(163.0)	54.4	(7.89)	4.84	23.2	-0.187	166.0	0.9994

TABLE 17

SUMMARY OF THE EFFECT OF A NOTCH ON LAMINATE 1 STATIC TENSION PROPERTIES AT ROOM TEMPERATURE
IN LABORATORY AIR

Radius of Hole, R = 3.175-mm(0.125-in.)

	Tensile Strength σ max, MPa	(ksi)	Weibull Parameters			Correlation Coefficient, R
			k	e	v	
Notched Coupons (Sample Size- 20)	284 11.2 3.9%	$(41.2)^a$ (1.62)	29.17	-0.056	41.83	0.9993
Un-Notched Coupons (Sample Size- 55)	567 28.5 5.0%	$(82.3)^a$ (4.13)	24.71	-0.278	83.98	0.9984

a - Average; Std Dev.; and Coeff. of Var., respectively

Average Un-notched Tensile Strength, σ_o: 567 MPa (82.3 ksi)

Expected Notched Tensile Strength, Based on Area, σ_{NA} : 405 MPa (58.8 ksi)

Expected Notched Tensile Strength, Average Stress Criteria [22] σ : 321 MPa (46.5 ksi)

Expected Notched Tensile Strength, Point Stress Criteria [22], σ_N : 289 MPa (41.9 ksi)

Experimentally Based Equivalent Notch Strength of an Infinite Width Laminate, σ_N^∞: 354 MPa (45.4 ksi)

Experimentally Based, σ_N^∞/σ_o: 0.55

Expected Ratio of σ_N^∞/σ_o, Based on Point Stress Criteria[22] : 0.56

Expected Ratio of σ_N^∞/σ_o, Based on Average Stress Criteria [22]: 0.62

notched coupons are shown in Figure 45. All of these coupons failed at the notch along ± 45° lines of fracture.

5.2 STATIC TENSION TEST RESULTS, HIGH TEMPERATURE

Un-notched

The effect of moisture and high temperature on the static, un-notched properties was evaluated. Laminate 1 and 2 un-notched coupons were conditioned at 82.2°C (180°F), 90% R.H. to equilibrium moisture content. After 92 days of conditioning, 20 coupons of each laminate were tested at 82.2°C (180°F) in laboratory air. The lack of high humidity did not significantly affect the moisture content as discussed in Section IV. The results of the static tension testing are listed in Appendix B, Tables B8 and B9, and summarized in Tables 18 and 19. Failure modes were unchanged from the room temperature, laboratory air testing results.

Notched

The effect of moisture and high temperature on the static, notched properties of laminate 1 was evaluated. Laminate 1 notched coupons were conditioned at 82.2°C (180°F), 90% R.H. to equilibrium moisture content. After conditioning, coupons were tested at 82.2°C (180°F) in laboratory air. Test results are given in Table 20 and listed in detail in Appendix B, Table B10. Failure modes were unchanged from the room temperature, laboratory air testing results.

5.3 STATIC COMPRESSION TEST RESULTS, ROOM TEMPERATURE

Unnotched

The compression test procedure was a modification of that used previously and reported in Reference 1. Essentially the procedure employed a fully side-supporting fixture designed to prevent column buckling and is described in detail in Reference 7 and is summarized in Section 2.5. Coupons were left tabbed on both ends rather than having the bottom end cut off. The new test procedure did not change the failure modes of the laminates. The failure
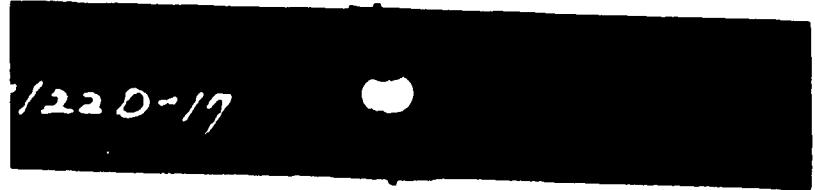
139 115R

a. Side View: Coupons 1SF1122-D17, 1SF1133-D4
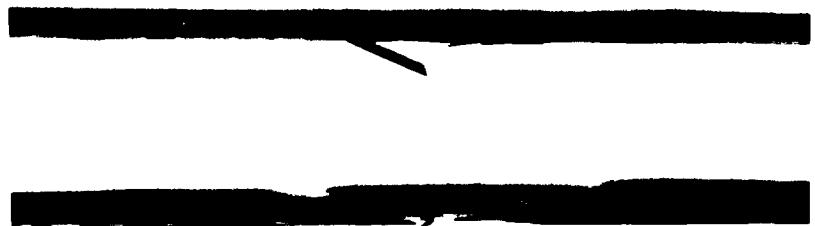
139 052R

b. Edge View: Coupons 1SF1122-D17, 1SF1133-D4

Figure 45. Representative Laminate 1 Notched Coupons which Failed
in Static Tension at Room Temperature in Laboratory Air

TABLE 18

SUMMARY OF STATIC TENSION UN-NOTCHED TEST RESULTS AT 82.2°C (180°F)

AFTER PRIOR-CONDITIONING AT 82.2°C (180°F) AT 90% R.H.

		Average Ultimate Stress, σ_{ult}, MPa (ksi)	Average Ultimate Strain, ϵ_{ult}, mm/mm in 50.8 mm	Average Initial Apparent Modulus of Elasticity, E_A, GPa (psi x 10^6)
Laminate 1	Average	556 (80.6)	.0109	51.3 (7.44)
	Std. Deviation	34.5 (5.00)	.00077	1.52 (0.22)
	Coeff. of Var. %	6.2	7.1	3.0
Laminate 2	Average	1135 (164.7)	.0112	101.4 (14.7)
	Std. Deviation	64.5 (9.36)	.00063	4.27 (0.62)
	Coeff. of Var. %	5.7	5.6	4.2

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TABLE 19

SUMMARY OF STATIC TENSION TEST PARAMETERS FOR UN-NOTCHED COUPONS TESTED AT 82.2°C (180°F) AFTER PRIOR-CONDITIONING AT 82.2°C (180°F) at 90% R.H.

	Number of Weibull Parameters	Weibull Coefficients			Correlation Coefficient, R
		k	e	v	
Laminate 1	3[a]	18.955	-0.5630	82.362	0.99687
	2[a]	18.698	0	82.889	0.99683
	2[b]	15.978	0	83.083	0.94821
Laminate 2	3[a]	19.921	-0.2398	168.024	0.99928
	2[a]	19.863	0	168.250	0.99928
	2[b]	18.725	0	169.071	0.98731

$$P(x) = \exp\left[-\left(\frac{x-e}{v-e}\right)^k\right]$$

a - Weibull coefficients obtained by iteration on R in single logarithmic space.

b - Weibull coefficients obtained directly by linear least square analysis in double logarithmic space, "Classical Solution".

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TABLE 20

SUMMARY OF THE EFFECT OF A NOTCH ON LAMINATE 1 STATIC TENSION PROPERTIES AT 82.2°C (180°F)

90% R.H. IN LABORATORY AIR

Radius of Hole, R = 3.175-mm(0.125-in.)

	Tensile Strength σ_{max}		Weibull Parameters			Correlation Coefficient, R
	MPa	(ksi)	k	e	v	
Notched Coupons (Sample Size 20)	270 26.4 9.8%	(39.2)[a] (3.83)	12.17	-0.447	40.51	0.9959
Un-Notched Coupons (Sample Size 20)	556 34.5 6.2%	(80.6)[a] (5.00)	18.95	-0.563	82.36	0.9969

a - Average; Std. Dev.; and Coeff. of Variation, Respectively

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locations remained unchanged for laminate 1 coupons and, as expected, were shifted towards the center of the laminate 2 coupons.

Laminate 1 coupons which failed in static compression, see Figure 46, exhibited no obvious damage prior to fracture although the stress-strain curve often was flat just prior to fracture indicating internal damage. Coupons usually failed at one location with the outer plies in the fracture region buckled out of plane. Extensive delamination usually occurred, but was limited over approximately 25 to 50-mm (1 to 2-in.) of the gage length in the vicinity of the fracture region. Fractures appeared on the outer plies along an irregular line along either a ±45° or 90° angle to the loading direction. Typical static compression failures of laminate 2 coupons are shown in Figure 47. These coupons failed along a predominantly ±45° line to the loading direction with delamination confined primarily to the fracture region. Some compression coupons fractured only in the outer plies along an approximately 90° line to the loading direction, Figure 47.

Tabulated static compression, un-notched, test results are listed in Appendix B, Tables B11 and B12, for coupons tested in laboratory air at room temperature. In these tables, the moduli are secant values. None of the coupons exhibited crushing prior to failure as did some of those reported in Reference 1. This lack of crushing was due to the change in test procedure. The compression test results of the two laminates are compared in Table 21. Laminate 1 showed the same ultimate strength as in tension; however, for both laminates, modulus was decreased in compression. This remained true even for the secant moduli of both laminates, at 241 and 483 MPa (35 and 70 ksi), respectively, which reflect the modulus of the straightest portion of the stress-strain curves.

Table 22 lists the Weibull parameters for these compression data sets. In Table 23, a comparison between the data reported in AFML-TR-76-241 (Reference 1) and that obtained in this program, is shown. As with the static tension results, the primary difference between the old and new batches of

139 114R

a. Side View: Coupons 2SF1121-C5, 1SF1117-A28
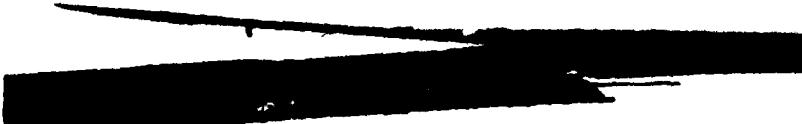
139 047R

b. Edge View: Coupons 2SF1121-C5, 1SF1117-A28

Figure 46. Representative Un-notched Laminate 1 Coupons which Failed in Static
Compression at Room Temperature in Laboratory Air

a. Side View: Coupons 2SF1133-A11, 1SF1137-A24
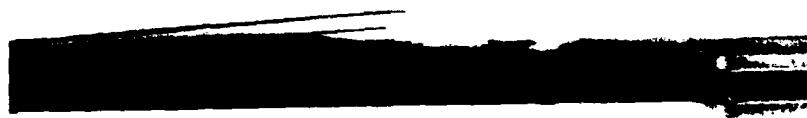
139 048R

b. Edge View: Coupons 2SF1133-A11, 1SF1137-A24

Figure 47. Representative Un-notched Laminate 2 Coupons which Failed in Static Compression at Room Temperature in Laboratory Air

TABLE 21

SUMMARY OF UN-NOTCHED STATIC COMPRESSION DATA OBTAINED IN ROOM TEMPERATURE, LABORATORY AIR

		Average Ultimate Stress, σ_{ult}, MPa (ksi)	Average Ultimate Strain, ϵ_{ult}, mm/mm, in 50.8 mm	Average Secant Modulus at Failure E_{sf}, GPa (psi x 10^6)
Laminate 1	Average	567 (82.3)	0.0135	42.1 (6.11)
	Std. Dev.	41.1 (5.96)	0.0014	1.52 (0.22)
	Coeff. of Var.	7.2%	10.3%	3.6%
Laminate 2	Average	1015 (147.2)	0.0132	77.2 (11.2)
	Std. Dev.	79.3 (11.5)	0.0014	4.69 (0.68)
	Coeff. of Var.	7.8%	10.8%	6.1%

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TABLE 22

SUMMARY OF ROOM TEMPERATURE, UN-NOTCHED COMPRESSION TEST PARAMETERS

	Number of Weibull Parameters	Weibull Coefficients			Correlation Coefficient R
		k	e	v	
Laminate 1	3[a]	15.632	-0.6305	84.552	0.99616
	2[a]	15.393	0	85.123	0.99611
	2[b]	14.420	0	85.100	0.95511
Laminate 2	3[a]	15.118	-0.9489	150.993	0.99681
	2[a]	14.925	0	151.833	0.99678
	2[b]	13.505	0	152.629	0.96380

$$P(x) = \exp\left| - \left(\frac{x-e}{v-e}\right)\right|^k$$

a - Weibull Coefficients obtained by iteration on R in Single Logarithmic space

b - Weibull Coefficients obtained directly by linear least square analysis in Double Logarithmic space.

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TABLE 23

COMPARISON OF ROOM TEMPERATURE, LABORATORY AIR, UN-NOTCHED COMPRESSION RESULTS
FOR DIFFERENT MATERIAL BATCHES

Lockheed Batch Code	Laminate 1		Laminate 2	
	MJ[a]	SF[b]	NH[a]	SF[a]
Avg. Ultimate Stress, σ_{ult}, MPa (ksi)	481 (69.7)[c] 46.2 (6.71) 9.6	567 (82.3) 41.1 (5.96) 7.2	786 (114.0) 41.1 (5.96) 5.4	1015 (147.2) 793 (11.5) 7.8
Avg. Ultimate Strain, ϵ, mm/mm in 50.8 mm	0.0110 0.0013 11.4	0.0135 0.0014 10.3	0.0098 0.00069 7.1	0.0132 0.0014 10.8
Avg. Secant Modulus to Failure, E_{sf} GPa (psi x 10^6)	–	42.1 (6.11) 1.5 (0.22) 3.6	79.3 (11.5) 2.6 (0.38) 3.3	77.2 (11.2) 4.7 (0.68) 6.1
Avg. Secant Modulus at 35 ksi (Laminate 1) or 70 ksi (Laminate 2) E_S GPa (psi x 10^6)	47.9 (6.95) 1.8 (0.26) 3.7	50.3 (7.30) 1.5 (0.22) 3.1	86.2 (12.5) 2.8 (0.41) 3.3	91.0 (13.2) 2.4 (0.35) 2.7

a - Material used in Contract F33615-75-C-5118, data reported in AFML-TR-76-241
b - Material used in present Contract, F33615-77-C-5045
c - Average, Std. Dev., and Coeff. of Var. % for each table entry

material lies in increased ultimate strength due to increased fiber strength and fiber volumn within the panels.

Notched

The effect of the notch on the laminate 1 room temperature compression proper-
ties are shown in Table 24 and tabulated in Appendix B, Table B13. Typical
compression fractures are shown in Figure 48. These coupons generally frac-
tured along a line 90° to the load direction.

5.4   STATIC COMPRESSION TEST RESULTS, HIGH TEMPERATURE

Un-notched

Appendix B, Tables B14 and B15 list the high temperature and moisture con-
tent (82.2°C (180°F) 90% R.H.) compression test data and Tables 25 and 26
summarize the results. Failure modes remained unchanged compared to the
room temperature, laboratory air, results except that the failure location
in laminate 2 coupons shifted more towards the tabs and less 45° failures
were observed.

Notched

Table 27 summarizes the compression results of notched laminate 1 coupons
tested after conditioning at 82.2°C (180°F), 90% R.H. Coupon test results
are tabulated in Appendix B, Table B16. Failure modes were similar to the
room temperature tests.

5.5   EFFECT OF ENVIRONMENT ON STATIC PROPERTIES

Un-notched

The static tension results as affected by high temperature and moisture con-
tent are compared to the room temperature, laboratory air results in Tables
28 and 29. The effect of high temperature and moisture content does not
seem to be statistically significant. This can be more clearly seen in
Figures 49 and 50, which show the three parameter Weibull fitting lines to

TABLE 24

SUMMARY OF THE EFFECT OF A NOTCH ON LAMINATE 1 STATIC COMPRESSION PROPERTIES AT ROOM TEMPERATURE

IN LABORATORY AIR

Radius of Hole, R = 3.175-mm(0.125-in.)

	Compressive Strength, σ_{max}, MPa (ksi)	Weibull Parameters k	e	v	Correlation Coefficient, R
Notched Coupons (Sample Size 20)	312 (45.2)[a] 24.8 (3.60) 8.0%	13.92	-0.130	46.55	0.9987
Un-Notched Coupons (Sample Size 20)	567 (82.3)[a] 41.1 (5.96) 7.2%	15.63	-0.631	84.55	0.9962

a – Average; Std. Dev.; and Coeff. of Var., respectively
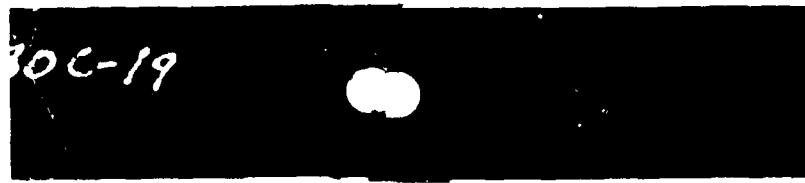
139 109R

a. Side View: Coupons 1SF1130-C19, 1SF1130-C27
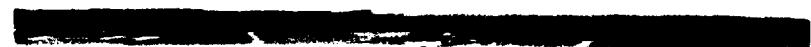
139 055R

b. Edge View: Coupons 1SF1130-C19, 1SF1130-C27

Figure 48. Representative Laminate 1 Notched Coupons which Failed in Static Compression at Room Temperature in Laboratory Air

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TABLE 25

SUMMARY OF STATIC COMPRESSION UN-NOTCHED TEST RESULTS AT 82.2°C (180°F)
AFTER PRIOR-CONDITIONING AT 82.2°C (180°F) AT 90% R.H.

		Average Ultimate Stress, σ_{ult}, MPa(ksi)	Average Ultimate Strain, ϵ_{ult}, $\frac{mm/mm}{in\ 50.8\ mm}$	Average Secant Modulus at Failure, E_{sf}, GPa (psi x 10^6)
Laminate 1	Average	483 (70.1)	.0114	42.9 (6.23)
	Std. Deviation	42.7 (6.20)	.0018	4.69 (0.68)
	Coeff. of Var.	8.8%	15.6%	10.9%
Laminate 2	Average	815 (118.2)	.0098	83.4 (12.1)
	Std. Deviation	82.7 (12.0)	.0015	6.34 (0.92)
	Coeff. of Var.	10.2%	15.5%	7.6%

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TABLE 26

SUMMARY OF STATIC COMPRESSION TEST PARAMETERS FOR UN-NOTCHED COUPONS TESTED AT 82.2°C (180°F) AFTER PRIOR-CONDITIONING AT 82.2°C (180°F) AND AT 90% R. H.

	Number of Weibull Parameters	Weibull Coefficients			Correlation Coefficient, R
		k	e	v	
Laminate 1	3[a]	13.151	-0.5572	72.195	0.99704
	2[a]	12.953	0	72.669	0.99700
	2[b]	11.439	0	73.088	0.97359
Laminate 2	3[a]	12.017	-2.5979	122.234	0.99216
	2[a]	11.538	0	124.349	0.99185
	2[b]	9.566	0	124.226	0.94768

$$P(x) = \exp\left[-\left(\frac{x-e}{v-e}\right)^{k} \right]$$

a - Weibull coefficients obtained by iteration on R in single logarithmic space.

b - Weibull coefficients obtained directly by linear least square analysis in double logarithmic space, "Classical Solution".

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TABLE 27

SUMMARY OF THE EFFECT OF A NOTCH ON LAMINATE 1 STATIC COMPRESSION PROPERTIES AT 82.2°C (180°F)

90% R.H. IN LABORATORY AIR

Radius of Hole, R = 3.175-mm(0.125-in.)

	Compressive Strength, σ_{max}, MPa (ksi)	Weibull Parameters			Correlation Coefficient, R
		k	e	v	
Notched Coupons (Sample Size 20)	276 (40.0)[a] 15.9 (2.30) 5.8%	20.1	-0.119	40.81	0.9987
Un-Notched Coupons (Sample Size 20)	483 (70.1)[a] 42.7 (6.20) 8.8%	13.15	-0.557	72.19	0.9970

a - Average; Std. Dev., and Coeff. of Var., respectively

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TABLE 28

SUMMARY OF UN-NOTCHED LAMINATE 1 STATIC TENSION TEST
RESULTS AT ROOM TEMPERATURE AND 82.2°C (180°F)

	Average Ultimate Stress, σ_{ult}, MPa(ksi)	Average Ultimate Strain, ϵ_{ult}, mm/mm in 50.8 mm	Average Initial Apparent Modulus of Elasticity E_A, GPa (psi x 10^6)
Results at room temperature in Laboratory air without prior conditioning	56.7 (82.3)[a] 28.4 (4.13)[b] 5.0%[c]	.0113 .00046 4.1%	53.3 (7.73) 1.94(0.28) 3.6%
Results at 82.2°C (180°F) in laboratory air after prior conditioning at 82.2°C (180°F) at 90% R.H.	556 (80.6) 34.5 (5.00) 6.2%	.0109 .00077 7.1%	51.3 (7.44) 1.52 (0.22) 3.0%

a, b, c - Average, standard deviation, and coefficient of variation, respectively

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TABLE 29

SUMMARY OF UN-NOTCHED LAMINATE 2 STATIC TENSION TEST
RESULTS AT ROOM TEMPERATURE AND 82.2°C (180°F)

	Average Ultimate Stress, σ_{ult}, MPa(ksi)	Average Ultimate Strain, ϵ_{ult}, mm/mm in 50.8 mm	Average Initial Apparent Modulus of Elasticity E_A, GPA (psi x 10^6)
Results at room temperature in laboratory air without prior-conditioning	1110 (161.0)[a] / 58.1 (8.42)[b] / 5.2%[c]	.0105 / .00046 / 4.4%	105.5 (15.3) / 2.62 (0.38) / 2.5%
Results at 82.2°C (180°F) in laboratory air after prior conditioning at 82.2°C(180°F) at 90% R.H.	1136 (164.7) / 64.5 (9.36) / 5.7%	.0112 / .00063 / 5.6%	101.4 (14.7) / 4.27 (0.62) / 4.2%

a, b, c - Average, standard deviation, and coefficient of variation, respectively

Figure 49. Probability of Survival Versus Ultimate Tensile Strength for Un-notched Laminate 1 Coupons

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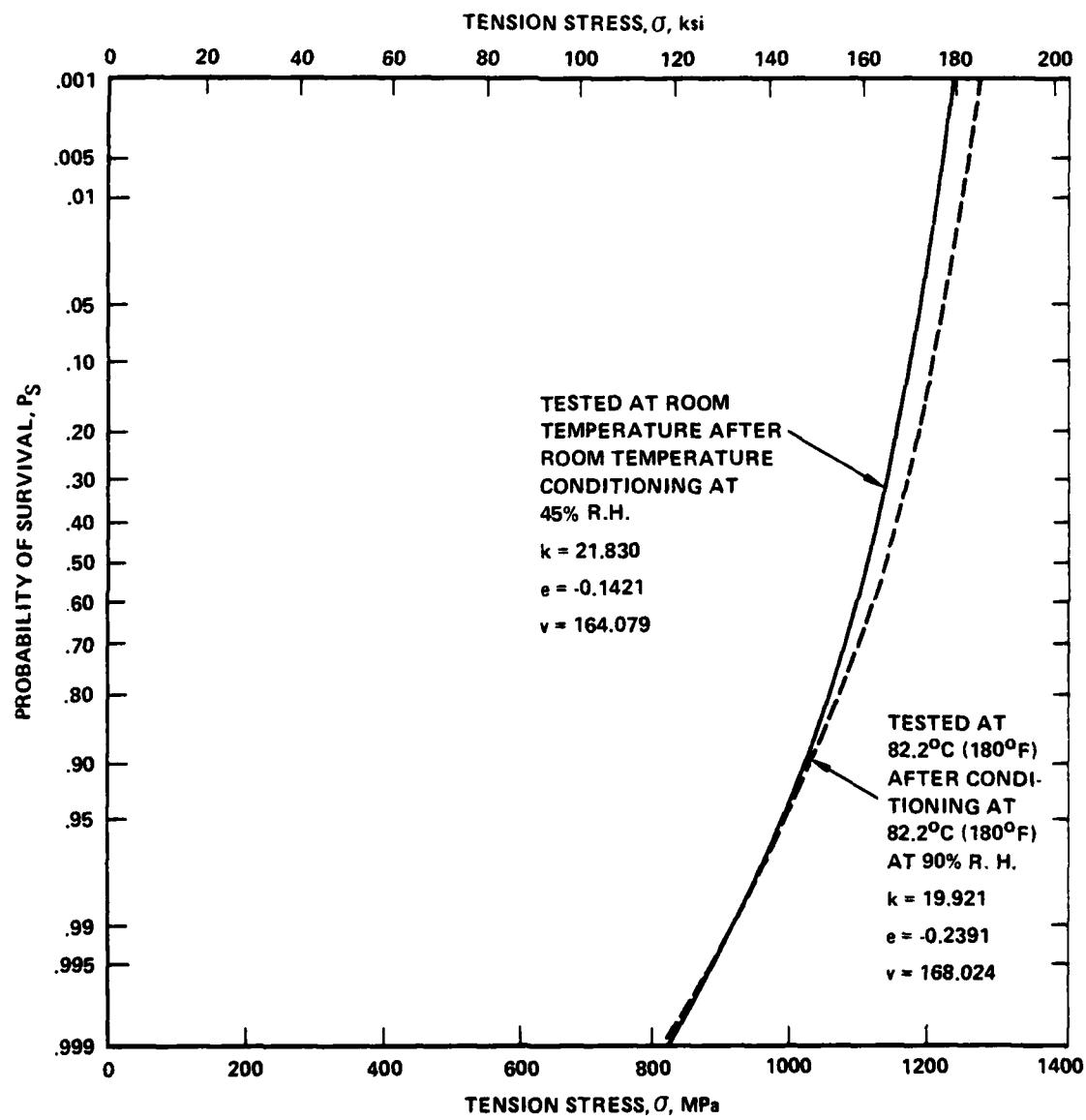
Figure 50. Probability of Survival Versus Ultimate Tensile Strength
for Un-notched Laminate 2 Coupons

the data summarized in Tables 28 and 29. The data points were left off for
clarity. The primary effect of the high temperature and moisture content on
the static tensile properties was a slight increase in scatter.

The static compression properties as affected by high temperature and moisture
content are compared to the room temperature, laboratory air results in Tables
30 and 31. The three parameter Weibull fits to the data summarized in Tables
30 and 31 are shown in Figures 51 and 52. Although there are small differences
in k, each of the two curves shown in Figures 51 and 52 are essentially paral-
lel, as expected. Statistically, the primary effect of the high temperature
and moisture content on the static compression properties of laminates 1 and
2 was a decrease in the characteristic life, v.

Notched

The notched static results of laminate 1 coupons as affected by high tempera-
ture and moisture content are compared to the room temperature, laboratory
air results in Tables 32 and 33. The effect of high temperature and moisture
content on the static tension properties was to increase the data dispersion.
This can be more clearly seen in Figure 53, which shows the three parameter
Weibull fitting lines to the data. The data points were left off for clarity.
The characteristic strength was not significantly affected by the high temper-
ature and moisture. Failure modes remained unchanged compared to the room
temperature, laboratory air results. The three parameter Weibull fits for
the compression data are also shown in Figure 53. The effect of high temper-
ature and moisture content on the static compression test properties of
laminate 1 notched coupons was somewhat different than for static tension.
Statistically, the primary effects of the high temperature and moisture con-
tent on the static compression properties of notched laminate 1 coupons was
a decrease in the characteristic life, v, accompanied by a decrease in data
dispersion. This result was different than the effect of temperature and
moisture on un-notched coupons. In that case, data dispersion did not change.

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TABLE 30

SUMMARY OF UN-NOTCHED LAMINATE 1 STATIC COMPRESSION TEST
RESULTS AT ROOM TEMPERATURE AND AT 82.2°C (180°F)

	Average Ultimate Stress, σ_{ult}, MPa(ksi)	Average Ultimate Strain, ϵ_{ult}, mm/mm in 50.8 mm	Average Secant Modulus at Failure, E_{sf}, GPa(psi x 10^6)	Average Secant Modulus at 35 ksi, E_{s35}, GPa (psi x 10^6)
Results at room temperature in laboratory air without prior-conditioning	567 (82.3)[a] 41.1(5.96)[b] 7.2%[c]	.0135 .0014 10.3%	42.1 (6.11) 1.52 (0.22) 3.6%	50.3 (7.30) 1.52 (0.22) 3.1%
Results at 82.2°C (180° (180°F) in laboratory air after prior-conditioning at 82.2°C (180°F) and at 90% R.H.	483 (70.1) 42.7 (6.20) 8.8%	.0114 .0018 15.6%	43.0 (6.23) 4.69 (0.68) 10.9%	51.4 (7.46) 2.07 (0.30) 4.0%

a, b, c, - Average, standard deviation, and coefficient of variation, respectively

TABLE 31

SUMMARY OF UN-NOTCHED LAMINATE 2 STATIC COMPRESSION TEST
RESULTS AT ROOM TEMPERATURE AND AT 82.2°C (180°F)

	Average Ultimate Stress σ_{ult}, MPa(ksi)	Average Ultimate Strain, ϵ_{ult}, mm/mm in 50.8 mm	Average Apparent Modulus of Elasticity. E_A GPa (psi x 10^6)	Average Secant Modulus at 70 ksi, E_{s70}, GPa (psi x 10^6)
Results at room temperature in laboratory air without prior-conditioning	1015 (147.2)[a] 79.3 (11.5)[b] 7.8%[c]	.0132 .0014 10.8%	77.2 (11.2) 4.69 (0.68) 6.1%	91.0 (13.2) 2.41 (0.35) 2.7%
Results at 82.2°C (180°F) in laboratory air after prior conditioning at 82.2°C (180°F) and at 90% R.H.	815 (118.2) 82.7 (12.0) 10.2%	.0098 .0015 15.5%	83.4 (12.1) 6.34 (0.92) 7.6%	93.8 (13.6) 3.24 (0.47) 3.4%

a, b, c - Average, standard deviation, and coefficient of variation, respectively

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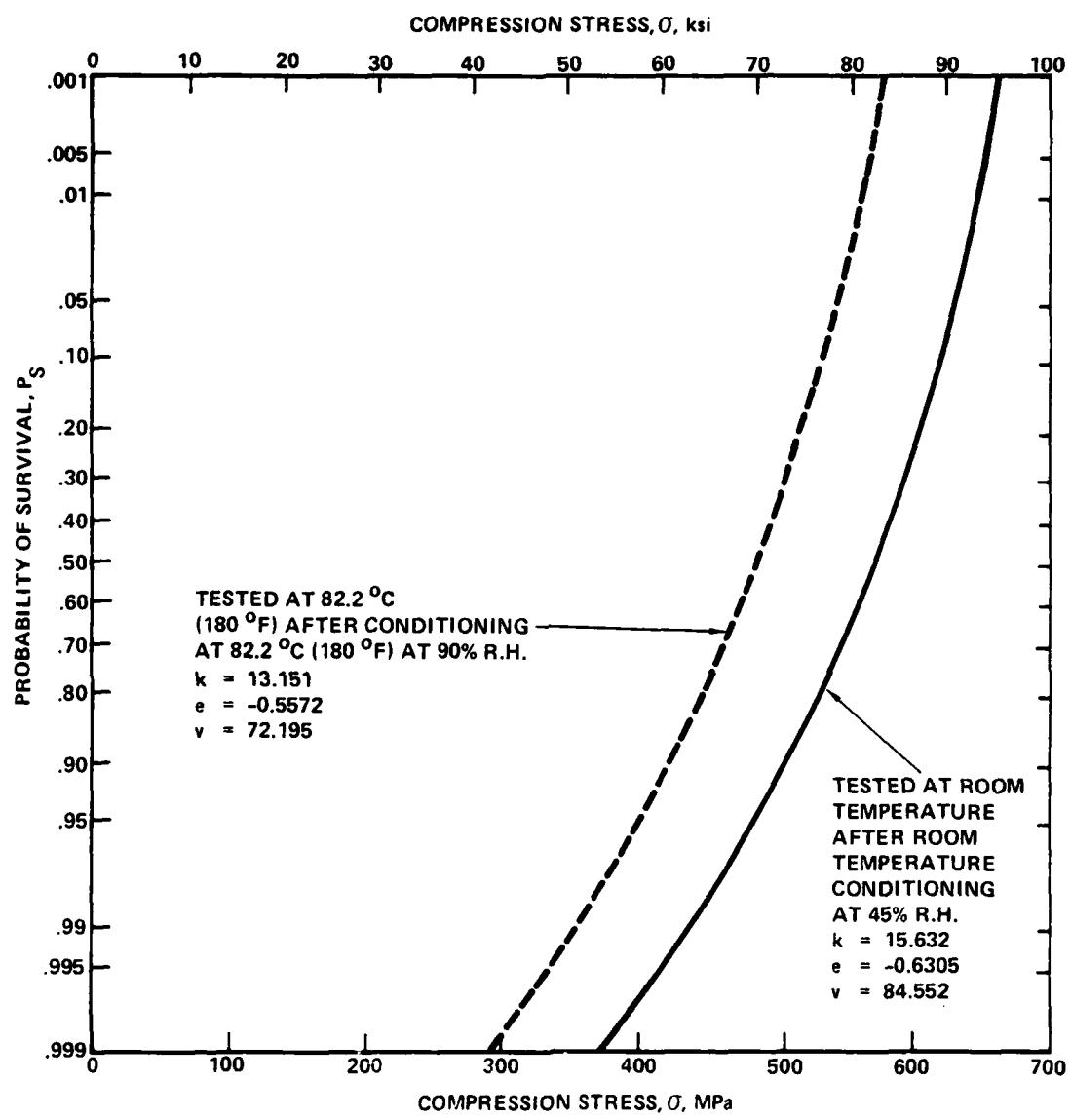
Figure 51.   Probability of Survival Versus Compressive Strength
for Un-notched Laminate 1 Coupon
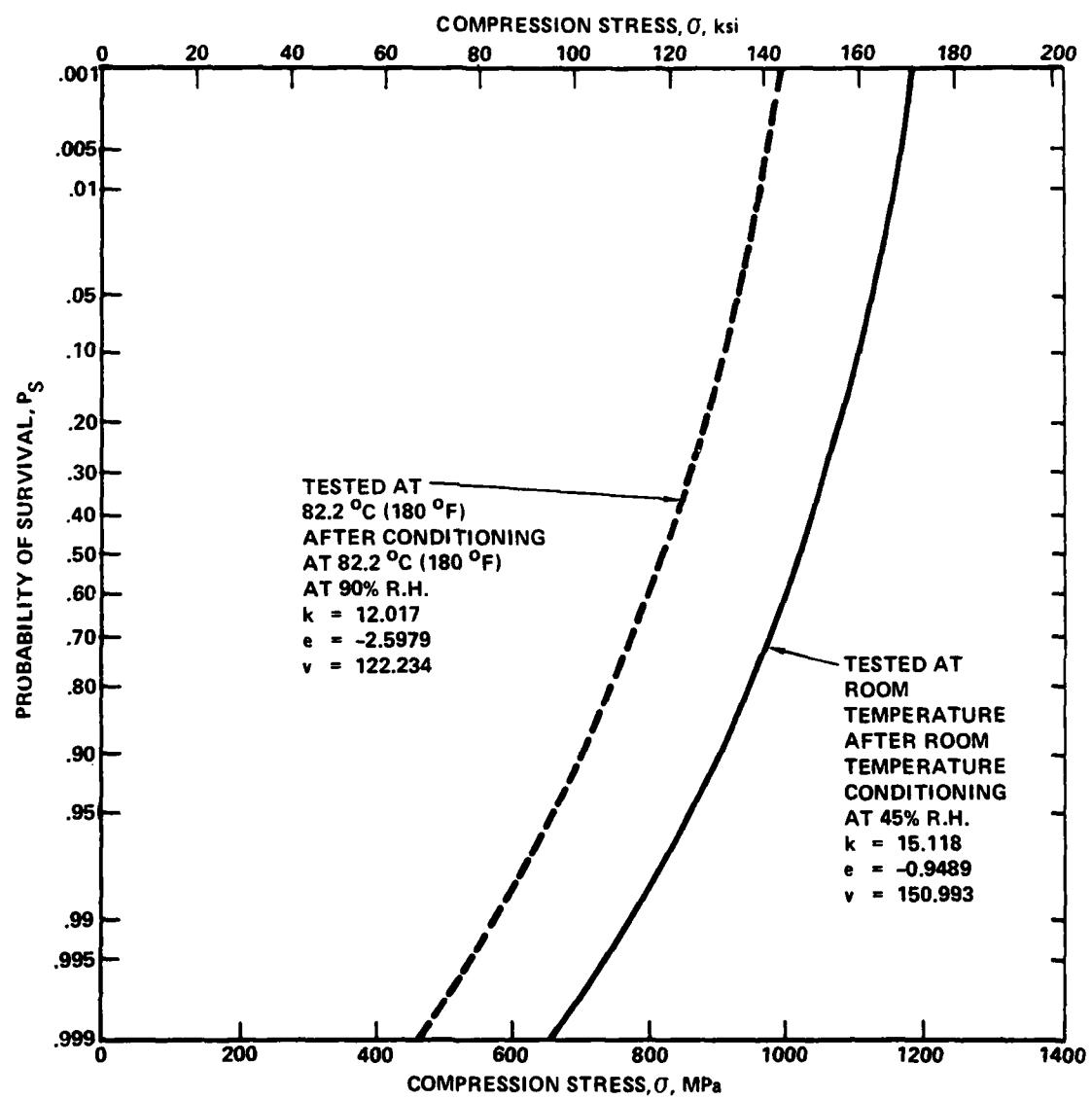
Figure 52. Probability of Survival Versus Compressive Strength
for Un-notched Laminate 2 Coupons

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TABLE 32

SUMMARY OF NOTCHED LAMINATE 1 STATIC TENSION TEST RESULTS

Ultimate Stress, σ_{ult}, MPa(ksi)		Number of Weibull Parameters	Weibull Analysis Results				
			Weibull Coefficients			Correlation Coefficient, R
			k	e	v	
Tested at 82.2°C (180°F) after prior conditioning at 82.2°C (180°F) at 90% R.H.	Avg. 270 (39.2)	3[a]	12.175	-0.4473	40.513	0.99587
	Std. Dev. 26.4(3.83)	2[a]	11.913	0	40.891	0.99578
	Coeff. of Var. % 9.77	2[b]	10.373	0	41.037	0.97440
Tested at room temperature in Laboratory Air	Avg. 284 (41.2)	3[a]	29.171	-0.0561	41.829	0.99934
	Std. Dev. 11.2 (1.62)	2[a]	29.092	0	41.884	0.99934
	Coeff. of Var. % 3.90	2[b]	26.911	0	41.937	0.98141

$$P(x) = \exp\left[-\left(\frac{x-e}{v-e}\right)^{k}\right]$$

a - Weibull coefficients obtained by iteration on R in single logarithmic space

b - Weibull coefficients obtained directly by linear least square analysis in double logarithmic space, "Classical Solution".

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TABLE 33

SUMMARY OF NOTCHED LAMINATE 1 STATIC COMPRESSION TEST RESULTS

Ultimate Stress σ_{ult}, MPa (ksi)		Number of Weibull Parameter	Weibull Analysis Results			
			Weibull Coefficients			Correlation Coefficient, R
			k	e	v	
Tested at 32.2°C (180°F) after prior conditioning at 82.2°C (180°F) at 90% R.H.	Avg. 276 (40.0)	3[a]	20.109	-0.1193	40.806	0.99867
	Std. Dev. 159 (2.30)	2[a]	19.991	0	40.919	0.99866
	Coeff. of Var. % 5.76	2[b]	17.990	0	41.083	0.97657
Tested at Room Temperature in Laboratory Air	Avg. 312 (45.2)	3[a]	13.917	-0.1300	46.547	0.99874
	Std. Dev. 2.48 (3.60)	2[a]	13.839	0	46.660	0.99874
	Coeff. of Var. % 8.00	2[b]	13.202	0	46.888	0.98641

$$P(x) = \exp\left[- \left(\frac{x-e}{v-e}\right)^k \right]$$

a – Weibull coefficients obtained by iteration on R in single logarithmic space

b – Weibull coefficients obtained directly by linear least square analysis in double logarithmic space, "Classical Solution".

ULTIMATE STRESS, σ, ksi

LAMINATE 1
NOTCHED TENSION
TEST RESULTS

LAMINATE 1
NOTCHED COMPRESSION
TEST RESULTS

TESTED AT 82.2°C
(180°F) AFTER PRIOR
CONDITIONING AT 82.2°C
(180°F) AT 90% R.H.

k = 20.109
e = -0.1193
v = 40.806

TESTED AT
ROOM TEMPER-
ATURE IN
LABORATORY AIR
AFTER ROOM
TEMPERATURE
CONDITIONING
AT 45% R.H.

TESTED AT 82.2°C
(180°F) AFTER PRIOR
CONDITIONING AT
82.2°C (180°F)
AT 90% R.H.

k = 12.175
e = -0.4472
v = 40.513

k = 29.171
e = -0.0561
v = 41.829

TESTED AT
ROOM TEMPERA-
TURE IN LABORATORY
AIR AFTER ROOM
TEMPERATURE
CONDITIONING
AT 45% R.H.

k = 13.917
e = -0.1300
v = 46.547

PROBABILITY OF SURVIVAL, P_S

ULTIMATE STRESS, σ, MPa
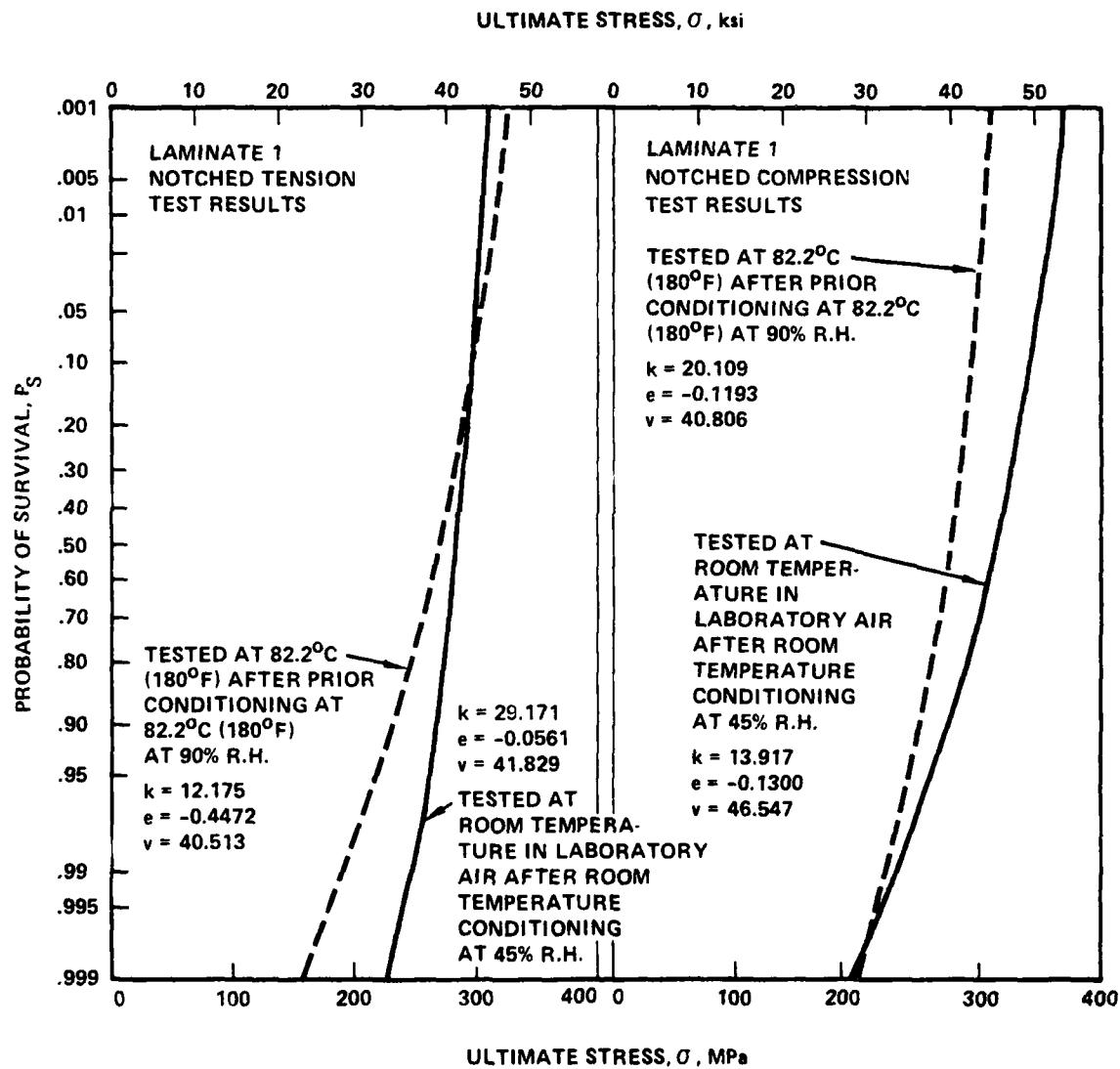
Figure 53.   Probability of Survival Versus Strength for Notched
Laminate 1 Coupons

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5.6 EFFECT OF STRAIN RATE ON STATIC PROPERTIES AND FATIGUE SCATTER

The fatigue results obtained previously and described in AFML-TR-76-242 [1] indicated the possibility that a much larger scatter in static tensile strength existed than that previously considered. The question was especially raised by the five laminate 2 coupons which failed on the first cycle of fatigue loading. Since all fatigue coupons were first loaded in tension, these failures could be considered as static tension failures. Therefore, the probability of survival of these coupons was calculated assuming they were static tension failures using the equation:

$$P(x) = 1/n$$

where   n = the number of static or fatigue coupons whose maximum first cycle tension stress equaled or exceeded x.

The value of failure stress, x, was precisely known for four of the five early failure coupons and within 5% for the other coupon. The failure load was determined using the permanent records of the high speed visicorder recorded for the first few load cycles of each fatigue coupon. Based on the above procedure, the P(x) values obtained are shown in Table 34. Also listed in Table 34 are the estimated strains to failure based upon the average apparent tensile modulus. The modulus at such high strain rates may have been slightly different; however, the lowest failure stress of the original 20 static failure coupons had a strain to failure of 0.0065-mm/mm; the same as coupon 728-19B which failed on the first load cycle. Three of the five coupons of Table 34 were from panel 1NH699 which may be significant considering that the C-scan record for that panel indicated some small anomolous regions.

Figure 54 shows the estimated distribution of static tensile strength data previously obtained [1] for laminate 2. The distribution indicates the possibility of an extended tail in the static strength data. The low static strength data could have been caused by any of four possibilities: (1) a strain rate/load interaction effect; (2) a material defect, (3) a geometric

TABLE 34

SUMMARY OF FIRST CYCLE FATIGUE FAILURES
OF UN-NOTCHED LAMINATE 2 COUPONS

Coupon ID	Ultimate Stress at σ_{ult}, MPa (ksi)	Estimated[a] Strain to Failure, ϵ_{ult}, mm/mm	Probability of Survival, P(x)
MJ 728-19B	687 (99.7)	.0065	.989
MJ 727-1C	633 (91.8)	.0060	.99
NH 699-1B	543 (78.8)	0051	.9906
NH 699-28C	540 (78.3)	.0051	.99065
NH 699-34B	483 (70)[b]	.0045	.994

a - Based on the average apparent tensile modulus of
   106 GPa (15.4 x 10^6 psi)

b - Estimated at 483 MPa (70 ksi) within 5%
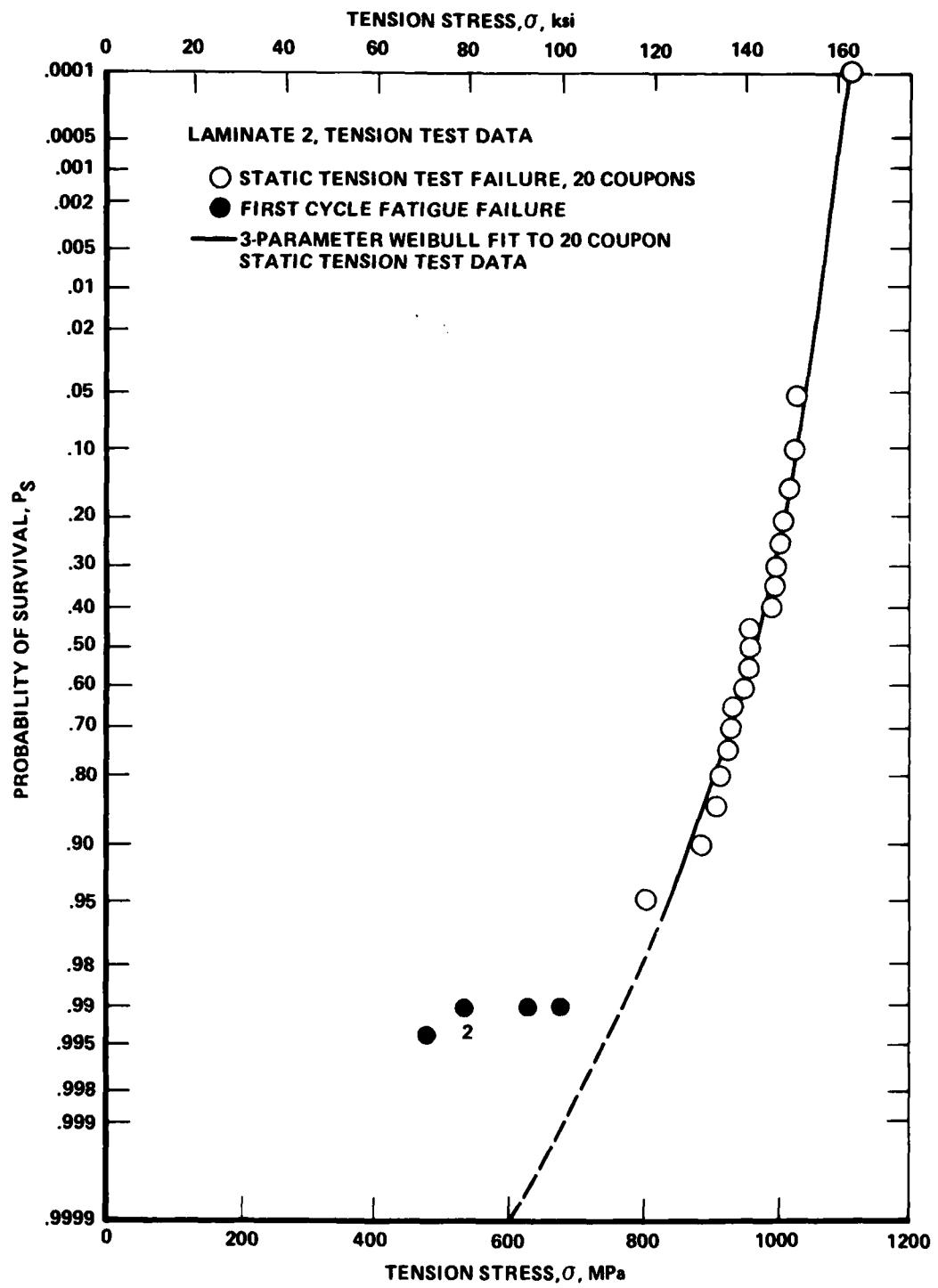
Figure 54. Distribution of Laminate 2 Static Tension Strength Data

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variation in the coupon; (4) an error in testing.

1) The strain rate during static tensile testing was approximately 0.015 mm/mm/min. while that during the first cycle of a fatigue test was approximately 6.0 mm/mm/min. or $\sim$ a 10^3 faster rate. This high strain rate may have caused a coupon to be more sensitive to any small local defect. However, as was shown in the previous study [1] by the static residual tension strength data, this effect is unlikely because no degradation in residual strength of the unfailed coupons was observed. A strain rate sensitivity may, however, exist which reduces the static strength. 2) Possibly rare, but not unique unobserved defects in the coupons caused the five first cycle fatigue failures, particularly in the case of those from panell NH 699. If this was true, such defects were not larger than the coupon gage length area because coupons which were situated in the panels above or below or on either side of the failed coupons had long fatigue lives or high static tension strengths. 3) Extremely small variations in the tab geometry ($\pm$ 0.0254-mm (0.001-in.)) may have caused load introduction problems and resultant early failure. 4) One possibility for an error in testing was an excessive torque on the grip bolts. Although this could have occurred, bolts on each laminate 2 coupon were uniformly tightened to 181 N·m (1600-in.·lbs) thus any variation would have to have been due to the specific load transfer caused by the particular geometry of each bolt. The possibility of an inadvertent coupon overload was prevented by maximum and minimum peak and valley detectors used on all tests which would have tripped if the load exceeded the preset maximum fatigue load. Additionally, visicorder records revealed no load overshoots.

To determine the cause of these laminate 2 first cycle fatigue failures, a large number of static coupons from a previously directed program [1] were tested in tension at two different strain rates using uniformly loading hydraulic grips. Both laminate 1 and 2 coupons were tested. In addition, the effect of a third and much higher strain rate on laminate 2 coupons was evaluated using a fatigue machine.

The results of this investigation are summarized in Table 35. The individual coupon data for these test results are given in Appendix B, Tables B17 to B25. The results listed in Table 35 were statistically evaluated to determine their significance. The three statistical procedures used were: 1) The F-test which evaluates the populations on the basis of their variances; 2) The t-test which examines the differences in the average strengths of the populations; 3) The Wald-Wolfowitz test which determines whether the two populations can be pooled into one population.

The statistical tests used will be described by giving a working example comparing the results for the laminate 2 coupons tested at 0.015 mm/mm/min to those tested at 0.6 mm/mm/min. The statistics of the two populations of the example are:

	Population A	Population B
Strain Rate, $\dot{\epsilon}$, mm/mm/min	0.015	0.6
Sample size, n	30	20
Standard Deviation, S	6.73	8.27
Mean, $\overline{X}$	143.6	135.0

F-test [23]

The quantity F is the ratio of the two sample variances,

$$F = S_A^2 / S_B^2 .$$

If the variances of Population A and Population B are identical at a significance level of $\alpha = 0.05$, F should lie between the boundaries defined by $F_{0.975}$ and $1/F_{0.975}$, for $n_A - 1$ and $n_B - 1$ degrees of freedom. For this case,

$$F = \frac{(6.73)^2}{(8.27)^2} = .662$$

$$n_A - 1 = 29$$

$$n_B - 1 = 19$$

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TABLE 35

EFFECT OF STRAIN RATE ON STATIC TENSILE PROPERTIES OF UN-NOTCHED LAMINATES 1 AND 2 AT ROOM TEMPERATURE
IN LABORATORY AIR

Laminate	Panel No. & Test Time	Strain Rate, $\dot\varepsilon$ mm/mm/min	Avg Ultimate Stress, σ ult MPa (ksi)		Avg Ultimate Strain, ε ult mm/mm in 50.8 mm	Initial Apparent Modulus of Elasticity, E_a, GPa (psi 10^6)		Final Apparent Modulus of Elasticity, E_b, GPa (psi x 10^6)	
1	10 Panels, 25 Coupons: 780, 782, 783, 784, 794, 796, 601, 603, 604, 606 (April 1975)		477 23.4 4.9%	(69.2)[a] (3.39)	.0096	52.7	(7.64)	44.5	(6.45)
	Panel 693, 5 Coupons (March, 1976)	0.015	482 39.7 8.2%	(69.9) (5.76)	.0095	52.2	(7.57)	43.6	(6.33)
	Panel 693, 10 Coupons (September, 1977)		507 25.3 5.0%	(73.5) (3.67)	.0106	49.9	(7.24)	43.9	(6.36)
	Panel 693, 10 Coupons (September, 1977)	0.600	470 21.0 4.5%	(68.2) (3.05)	-	-		-	
2	4 Panels, 20 Coupons: 696, 699, 727, 728 (March, 1976)		977 64.0 6.6%	(141.7) (9.29)	.0092	106.2	(15.4)	-	
	4 Panels, 30 Coupons: 696, 699, 727, 728 (September 1977)	0.015	990 46.4 4.7%	(143.6) (6.73)	.0102	97.9	(14.2)	-	
	4 Panels, 20 Coupons: 696, 699, 727, 728 (September, 1977)	0.600	931 57.0 6.1%	(135.0) (8.27)	-	-		-	
	4 Panels, 20 Coupons: 696, 699, 727, 728 (October 1977)	6.000	881 84.8 9.6%	(127.9) (12.3)	-	-		-	
	4 Panels, 19 Coupons: 696, 699, 727, 728 (October, 1977) (in Fatigue Machine)	0.015	919 72.4	(133.3) (10.5)	-	-		-	

a - Average; Std. Dev., Coef. of Var. %

and from a statistical table [24],

$$F_{0.975} = 2.4$$

$$1/F_{0.975} = .417 .$$

Therefore F for the two populations did lay within the defined interval and the variances can be assumed to be identical, within a 0.05 risk of error. This indicated that the two populations may belong to the same population, i.e., have the same scatter or dispersion.

t-test [23]

This test examines the difference in the average strength of the two populations. If they differ, one may conclude that they do not belong to the same population. The absolute difference between the two means is calculated by

$$D_{\overline{X}} = |\overline{X}_A - \overline{X}_B| .$$

If the two means are identical, $D_{\overline{X}}$ should not exceed u, defined as follows for $\alpha = 0.05$,

$$u = t_{0.975} S_p \sqrt{\frac{n_A + n_B}{n_A n_B}} ,$$

where $t_{0.975}$ with $n_A + n_B - 2$ degrees of freedom is found from Table 9.6.4.5 of Reference 3, and

$$S_p = \sqrt{\frac{(n_A - 1) S_A^2 + (n_B - 1) S_B^2}{n_A + n_B - 2}} .$$

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For this case,

$$D_{\overline{X}} = |143.6 - 135.0| = 8.6$$

$$n_A + n_B - 2 = 48$$

$$t_{0.975} = 2.010$$

$$S_p = \left[\frac{(30-1)(6.73)^2 + (20-1)(8.27)^2}{30 + 19 - 2} \right]^{1/2}$$

$$= 7.378$$

$$u = (2.010)(7.378)\left(\frac{30 + 20}{30 \times 20}\right)^{1/2} = 4.28 .$$

Since $D_{\overline{X}} > u$, one may conclude that the means of the two populations were not the same within a 0.05 risk of error.

Wald-Wolfowitz Test [23]

Using the two series of data points from Populations A and B, the question of whether or not the two populations could be combined by applying the run test was examined. The two samples were pooled in rank order. If the strength was from Population A, a 0 was entered, if from Population B, a 1. This gave the following array for the combined 50 data points.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	1	1	1	0	0	1	1	1	0	1	0	0	1	0	1	1	0	0	1	1	1	0	0	0

26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	1	1

Application of the above statistical procedures to pairs of the static strength populations tabulated in Appendix B, Tables B17 to B35 and in Table 35, led to the results summarized in Table 36. *The conclusions based on the results listed in Tables 35 and 36 are: 1) higher strain rates led*

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to decreased strength in both laminates; (2) the effect of coupon storage
time is to decrease the modulus, and increase the strain to failure; 3) the
dispersion of the data may increase with increasing strain rate; 4) grip
type changes the strength distribution of laminate 2 coupons. The overall
conclusions, based on this summary and the fact that only laminate 2 coupons
experienced first cycle fatigue failures, are: 1) that strain rate has an
important effect on static strength; 2) that the cause of the laminate 2
coupons' first cycle fatigue failures is related to a strain rate/strain
transfer interaction being more severe than that for laminate 1 coupons.

Figure 54 showed the distribution of laminate 2 static strength and that the
first cycles fatigue failures did not fit this distribution. Figure 55
shows this same data, but also the distribution of the static strength
population at $\dot{\varepsilon} \sim 6$ mm/mm/min obtained using a fatigue machine. This figure
strongly indicates that the observed first cycles failures can be qualita-
tively explained by the sensitivity of laminate 2 coupons to strain rate and
load transfer.

TABLE 36

STATISTICAL ANALYSIS RESULTS OF COMPARING

VARIOUS UN-NOTCHED STATIC STRENGTH POPULATIONS

Comparison Type	Test Type		
	F-test	t-test	Wald-Wolfowitz
Laminate 1 0.6 $\dot{\epsilon}$ compared to 0.015 $\dot{\epsilon}$ (Hydraulic Grips)	No[a]	Yes	Yes
Laminate 2 0.6 $\dot{\epsilon}$ compared to 0.015 $\dot{\epsilon}$ (Hydraulic Grips)	No	Yes	Yes
Laminate 2 6.0 $\dot{\epsilon}$ (Fatigue Grips) compared to 0.015 $\dot{\epsilon}$ (Hydraulic Grips)	Yes	Yes	Yes
Laminate 2 6.0 $\dot{\epsilon}$ compared to 0.015 $\dot{\epsilon}$ (Both tested using Fatigue Grips)	No	No	Yes
Laminate 2 0.015 $\dot{\epsilon}$ tested in fatigue machine compared to 0.015 $\dot{\epsilon}$ tested in static machine	Yes	Yes	Yes

a) A "Yes" indicates that the populations can be said to differ on the basis of that test with a risk of error of 0.05. A "No" indicates that they cannot be said to differ.

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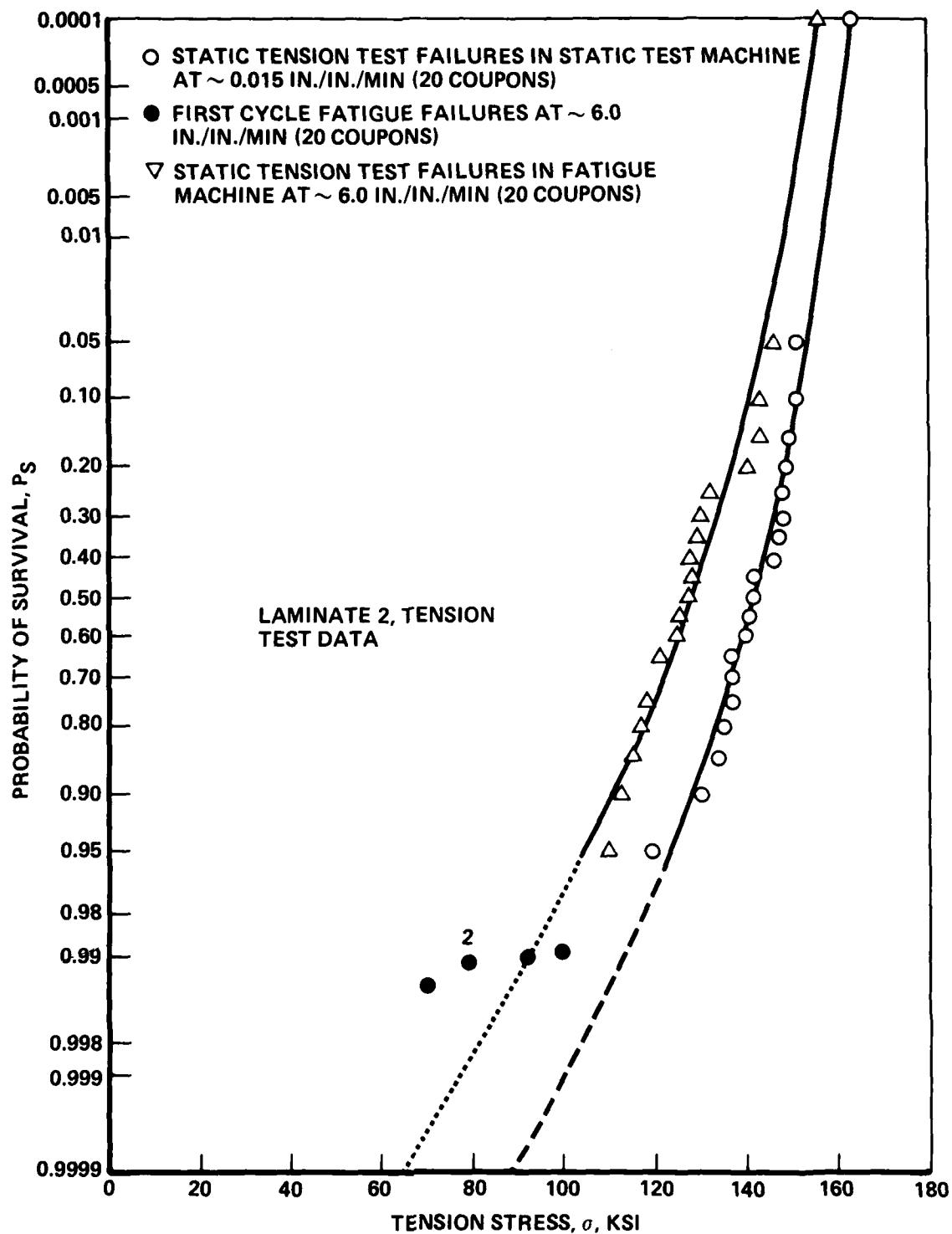
Figure 55. Un-notched Laminate 2 Static Tension Test Data at Different Strain Rates

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SECTION VI

FATIGUE RESULTS

The fatigue study was divided into two major sub-tasks. In the first task,
the general stress-life, S-N, characteristics of the two laminates were devel-
oped under both tension-tension and tension-compression loading. The S-N
scans were conducted by testing three coupons at each of several maximum
stress levels. Subsequent to determining the general characteristics of the
S-N behavior, the extent of fatigue scatter was determined by conducting
15 or more tests at several specifically chosen maximum stress levels.

A major consideration prior to the fatigue test program was which of the
loading variables pertinent to fatigue should be held constant. The variables
considered were: load ratio, R; maximum stress, σ_{max}; stress range $\Delta\sigma$; and
minimum stress, σ_{min}. Any one of these variables could have been held
constant and two others allowed to vary while the effect of the fourth was
evaluated.

Coupled with the considerations of loading variables was the practical
problem that these laminates acted like thin columns, thus limiting the
maximum compression that could be reached without buckling. For these tests
buckling was defined as 0.0254-mm (0.001-in.) deflection out-of-plane any-
where within the gage length. For laminate 1 with two buckling restraints,
this criterion limited the maximum compression stress in fatigue to -110 MPa
(-16 ksi) identical to that recorded previously [1] for coupons manufactured
from material batch MJ and NH. Laminate 2 with two restraints was limited
to -207 MPa (-30 ksi) Based on the practical test restraint of buckling,
fatigue tests conducted at constant R values were considered impractical
because σ_{max} would be restricted in magnitude. All fatigue tests were
thus conducted at the same constant minimum stress previously used (0 or
-110 MPa (0 or -16 ksi) for laminate 1 and 0 or -207 MPa (0 or -30 ksi)

for laminate 2) and the maximum stress was allowed to vary. This procedure permitted direct comparison of results based on σ_{max} or $\Delta\sigma$ as well as limited study of the effect of R. For the laminate 1 notched coupons the same limiting compressive stress based on gross area was selected.

For tension-tension tests, failure was defined as breakage of the coupon; for tension-compression tests, failure was defined as coupon breakage or inability to sustain compression load due to severe delamination. Investigation showed that if the latter failure definition was used, breakage of the specimen could be forced by the addition of a few more cycles.

An observation of importance was that significant visible delamination often did not occur in tension-tension testing prior to failure, but when such delamination did occur, the remaining cycles to failure could be either small or large. However, for tension-compression testing when delamination was noted prior to failure, normally 90% or more of the coupon life was exceeded. Therefore, in the future, delamination may possibly be a more useful definition of failure in tension-compression fatigue while coupon breakage may be more useful for tension-tension fatigue. The observation on delamination is important because coupons tested at 82.2°C (180°F), 90% R.H. displayed delamination much earlier in fatigue life than those tested at room temperature.

Another problem of major concern was the previously observed [1] increase in coupon temperature during fatigue cycling. Both laminates were studied [1] by measuring coupon temperature at the tab midpoint; on the coupon surface near each tab; and on the coupon surface at the center of the gage length. For laminate 1, the temperature of tension-tension fatigue coupons remained constant at the laboratory air temperature until a cycle count was reached approximately equal to when delamination was noted. At this point, temperature quickly increased approximately 4° to 8°C (8° to 15°F) and remained constant to failure. The tension-compression coupons of laminate 1 exhibited a temperature rise of 4° to 8°C (8° to 15°F) immediately after test commencement, but afterwards the temperature remained constant until failure. In

contrast, laminate 2 coupons tested under both conditions exhibited a small temperature rise (3° to 8°C (5° to 15°F)) within the gage length, but a large rise (up to 39°C (70°F)) within the tabs. The rise of tab temperature was due to the large strains induced in the adhesive and resulted in creep of the tab relative to the coupon and tab pull-off. Therefore, grip ends of laminate 2 coupons were cooled with forced room temperature, shop air to keep the grip temperature near room air temperature. In the high temperature tests, the problem of coupon temperature increase due to fatigue caused some difficulty in maintaining temperature in laminate 2 tension-compression tests. This problem was solved by compensating the temperature controls.

Fatigue failure modes of the two laminates appeared to differ from each other as well as from static tension and compression failure modes. They were, in all cases, similar to those previously observed [1]. Un-notched laminate 1 coupons tested in tension-tension (T-T) fatigue at room temperature failed due to extensive delamination which started between the two -45° layers at the free edge and progressed inwards. Figure 56 shows two coupons which failed at relatively short lives and exhibit rather localized delamination. Figure 57 shows one coupon which failed at relatively long life, and correspondingly greater delamination, and a second coupon which remained unfailed at 3×10^6 cycles and displays end-to-end delamination. Un-notched laminate 1 coupons tested in tension-compression (T-C) fatigue at room temperature failed similarly to those tested in T-T, Figures 58 and 59, but large out-of-plane buckling of the outer four plies occurred soon after the onset of delamination resulting in reduced fatigue lives at the lower σ_{max} levels.

Fatigue damage development and progression in the notched laminate 1 coupons tested under T-T loading at room temperature was entirely dominated by the hole. Damage was first visible as fine surface cracks parallel to the 0° fibers and load direction, Figure 60. For some coupons, such cracks barely

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Fatigue damage development and progression in the notched laminate 1 coupons tested under T-T loading at room temperature was entirely dominated by the hole. Damage was first visible as fine surface cracks parallel to the 0° fibers and load direction, Figure 60. For some coupons, such cracks barely

119 117F

a. Side View: Coupons 1SF1117-C14, 0 to 483 MPa (70 ksi),
   2SF1132-A23, 0 to 448 MPa (65 ksi)

139 07TR
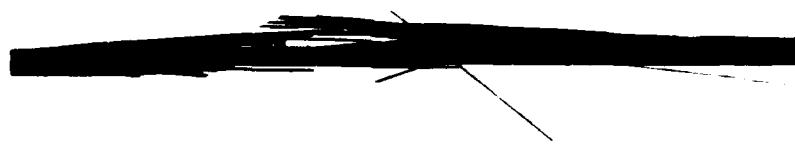
b. Edge View: Coupons 1SF1117-C14, 0 to 483 MPa (70 ksi)
   2SF1132-A23, 0 to 448 MPa (65 ksi)

Figure 56. Representative Un-notched Laminate 1 Coupons which Failed at
          Short Lives after Tension-Tension Fatigue at Room Temperature
          in Laboratory Air

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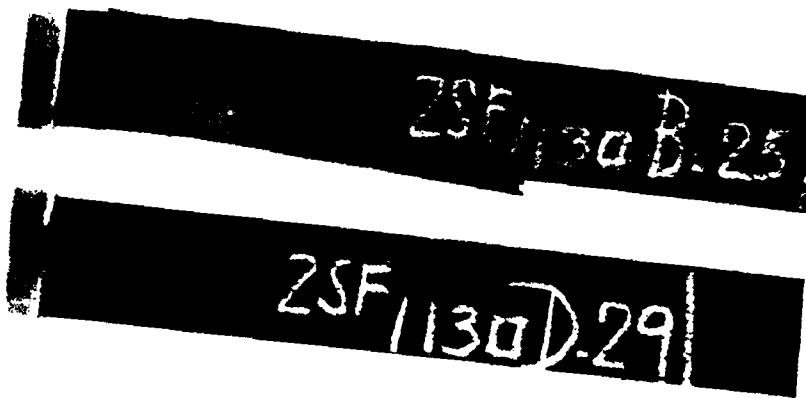
a. Side View: Coupons 2SF1130-B25, 0 to 310 MPa (45 ksi);
2SF1130-D29, 0 to 276 MPa (40 ksi)

139 107R

b. Edge View: Coupons 2SF1130-B25, 0 to 310 MPa (45 ksi);
2SF1130-D29, 0 to 276 MPa (40 ksi)

139 072R

Figure 57. Representative Un-notched Laminate 1 Coupons which had Long
Lives in Tension-Tension Fatigue at Room Temperature in
Laboratory Air

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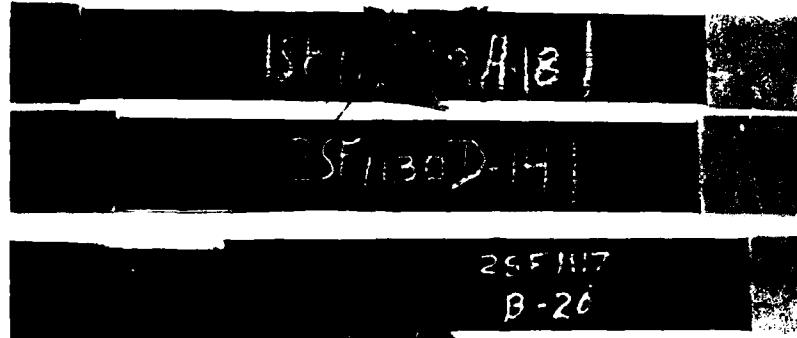
a. Side View: Coupons 1SF1132-A18, -110 to 483 MPa (-16 to 70 ksi); 521 Cycles; 2SF1130-D14, -110 to 414 MPa (-16 to 60 ksi), 5060 Cycles; 2SF1117-B20, -110 to 379 MPa (-16 to 55 ksi), 14300 Cycles
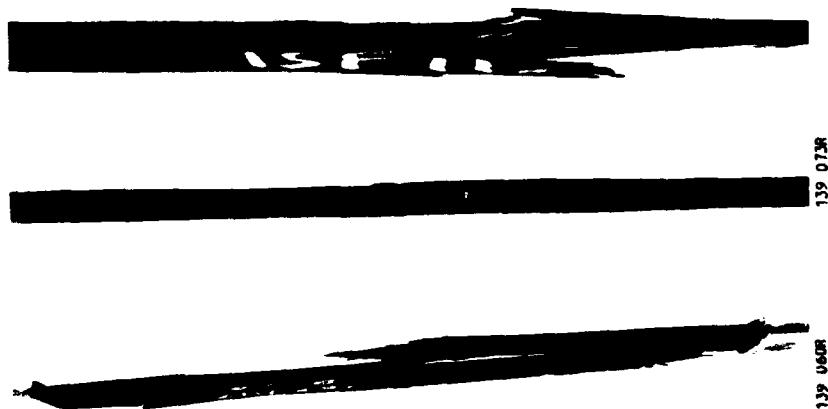
b. Edge View: Coupons 1SF1132-A18, 2SF1130-D14, 2SF1117-B20

Figure 58. Representative Un-notched Laminate 1 Coupons which Failed at Short Lives after Tension-Compression Fatigue at Room Temperature in Laboratory Air

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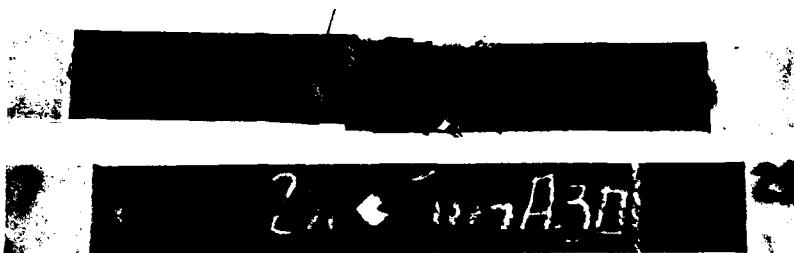
139 116R

a. Side View: Coupons 1SF1133-D9, -110 to 310 MPa (-16 to 45 ksi), 61,794 Cycles; 2SF1117-A30, -110 to 241 MPa (-16 to 35 ksi), 305500 Cycles

139 076R

139 0694
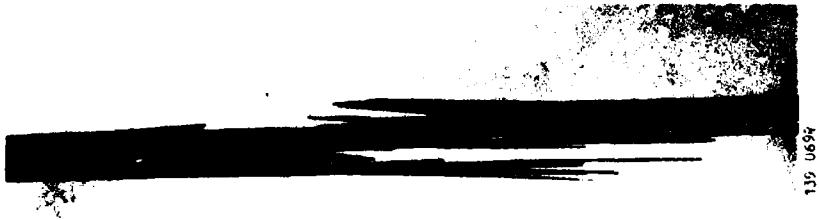
b. Edge View: Coupons 1SF1133-D9, 2SF1117-A30

Figure 59. Representative Un-notched Laminate 1 Coupons which Failed at Long Lives after Tension-Compression Fatigue at Room Temperature in Laboratory Air

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135 057R

Side View: Coupon 1SF1130-A16, 0 to 193 MPa (28 ksi), Unfailed at 1 x 10^6 Cycles

Figure 60. Unfailed Laminate 1 Notched Coupon Showing Initiation of Hole Delamination

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progressed before fracture through the hole occurred, Figure 61. In other coupons, the cracks extensively propagated parallel to the loading direction, bounded essentially by the width of the hole, before fracture through the hole occurred, Figure 61. Subsurface, the cracks appeared to be due to delamination between the -45° plies. Fatigue damage and growth in the notched laminate 1 coupons tested under T-C loading at room temperature was similar to those under T-T loading except that extensive parallel cracking could occur away from the hole due to the compression loading, Figure 62. Fractures were similar to T-T loading, Figure 63, however, many coupons failed due to inability to sustain any compressive loading, Figure 62.

Laminate 2 coupons exhibited no early delaminations during fatigue under either T-T or T-C loading. At high σ_{max} levels, fatigue failures were similar to tensile failures (observe coupon SF1137-C12 in Figure 64) while at lower σ_{max} levels the outer 0° plies shredded eventually followed by sudden failure which sometimes resulted in massive delamination, Figure 64. Damage initiation and growth was similar for coupons tested in T-C loading, Figures 65 and 66.

Failure modes of coupons tested at 82.2°C (180°F), 90% R.H. were in all cases the same as those tested at room temperature. The only difference was that the type of damage which led to failure occurred much earlier in fatigue life for coupons tested at the same load levels. All laminate 1 and 2 coupons tested in tension-compression fatigue at either room temperature or high temperature failed during the compression load excursions. Laminate 1 coupons and most laminate 2 coupons displayed fatigue failure modes which appeared quite different from static tension or compression failure modes.

6.1   FATIGUE STRESS-LIFE SCAN RESULTS

The data for all the plots in this subsection are tabulated in Appendix C.

Laminate 1

The results of the stress-life study used to determine the general form of the fatigue behavior of un-notched laminate 1 coupons are shown in Figures 67
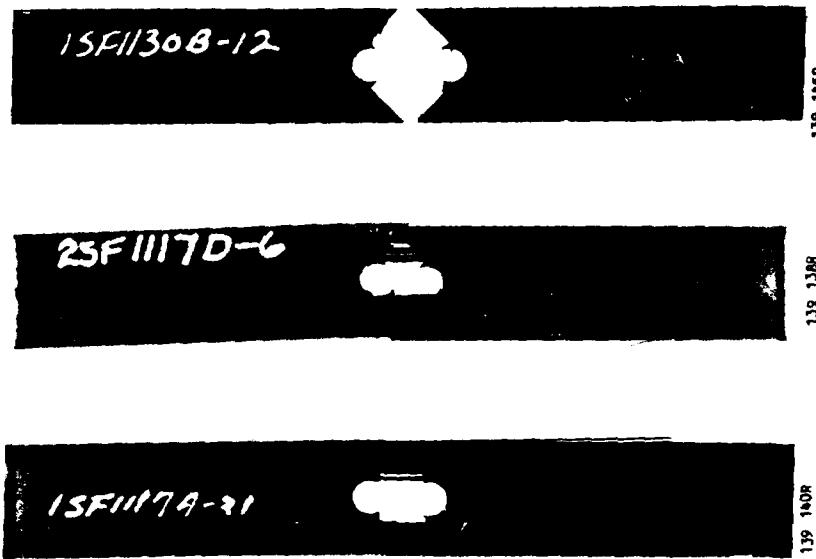
a. Side View: Coupons 1SF1130-B12, 0 to 248 MPa (36 ksi) 36 cycles: 2SF1117-D6, 0 to 248 MPa (36 ksi), 104,300 Cycles; 1SF1117-A31, 0 to 221 MPa (32 ksi), 483,460 Cycles

b. Edge View: Coupons 1SF1130-B12, 2SF1117-D6, 1SF1117-A31

Figure 61. Representative Laminate 1 Notched Coupons Failed in Tension-Tension Fatigue at Room Temperature in Laboratory Air
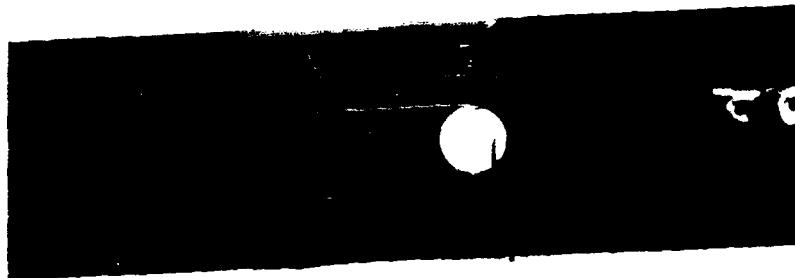
139 058R

a. Side View: Coupon 1SF1122-D22, -110 to 138 MPa
    (-16 to 20 ksi), 302,229 Cycles

139 079R

b. Edge View: Coupon 1SF1122-D22

Figure 62. Representative Laminate 1 Notched Coupon which Failed at
            Long Life After Tension-Compression Fatigue at Room
            Temperature in Laboratory Air

146

139 1446

a. Side View: Coupons 1SF1121-D6, -110 to 248 MPa (-16 to 36 ksi), 8600 Cycles; 2SF1122-C17, -110 to 193 MPa (-16 to 28 ksi), 51,306 Cycles
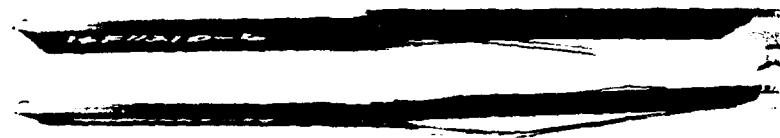
139 061R

b. Edge View: Coupons 1SF1121-D6, 2SF1122-C17

Figure 63. Representative Laminate 1 Notched Coupons which Failed at Short Lives After Tension-Compression Fatigue at Room Temperature in Laboratory Air

147
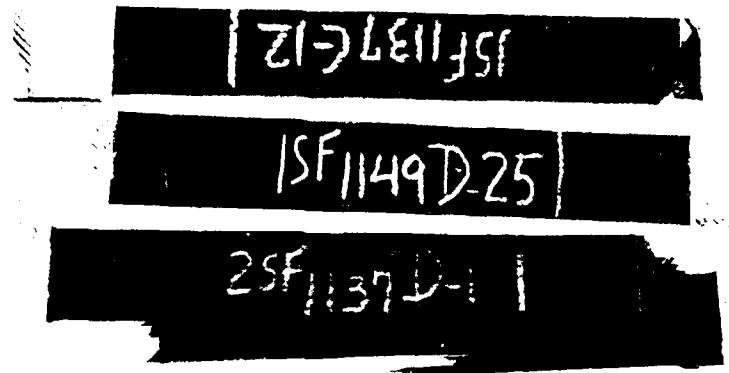
139 119R

a. Side View: Coupons 1SF1137-C12, 0 to 827 MPa (0 to 120 ksi), 122 Cycles; 1SF1149-D25, 0 to 827 MPa (0 to 120 ksi), Unfailed at 1 x 10^6 Cycles; 2SF1137-D1, 0 to 758 MPa (0 to 110 ksi), 889257 Cycles
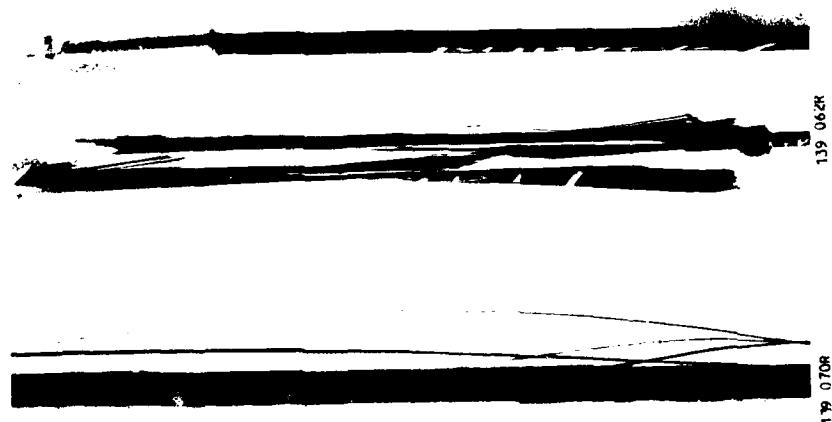
b. Edge View: Coupons 1SF1137-C12, 2SF1137-D1, 1SF1149-D25

Figure 64. Representative Laminate 2 Coupons Fatigue Cycled under Tension-Tension Loading at Room Temperature in Laboratory Air
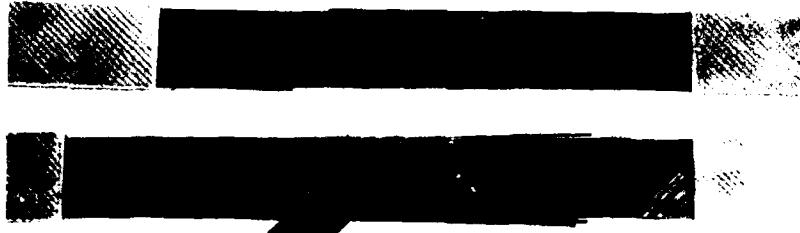
119 1064

a. Side View: Coupons 2SF1149-D9, -207 to 896 MPa (-30 to 130 ksi), 28 cycles; 2SF1137-D23, -207 to 758 MPa (-30 to 110 ksi), 394449 cycles

119 0718

b. Edge View: Coupons 2SF1149-D9, 2SF1137-D23

Figure 65. Representative Laminate 2 Coupons which Failed in Tension-Compression Fatigue at Room Temperature Laboratory Air

a. Side View: Coupon 1SF1137-C23, -207 to 689 MPa (-30 to 100 ksi)
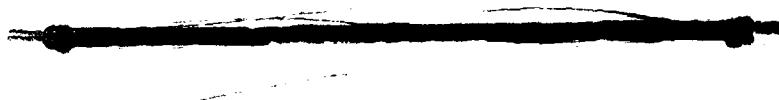
139 066

b. Edge View: Coupon 1SF1137-C23

Figure 66. Representative Laminate 2 Coupon Unfailed at 1×10^6 Cycles After Tension-Compression Fatigue at Room Temperature in Laboratory Air
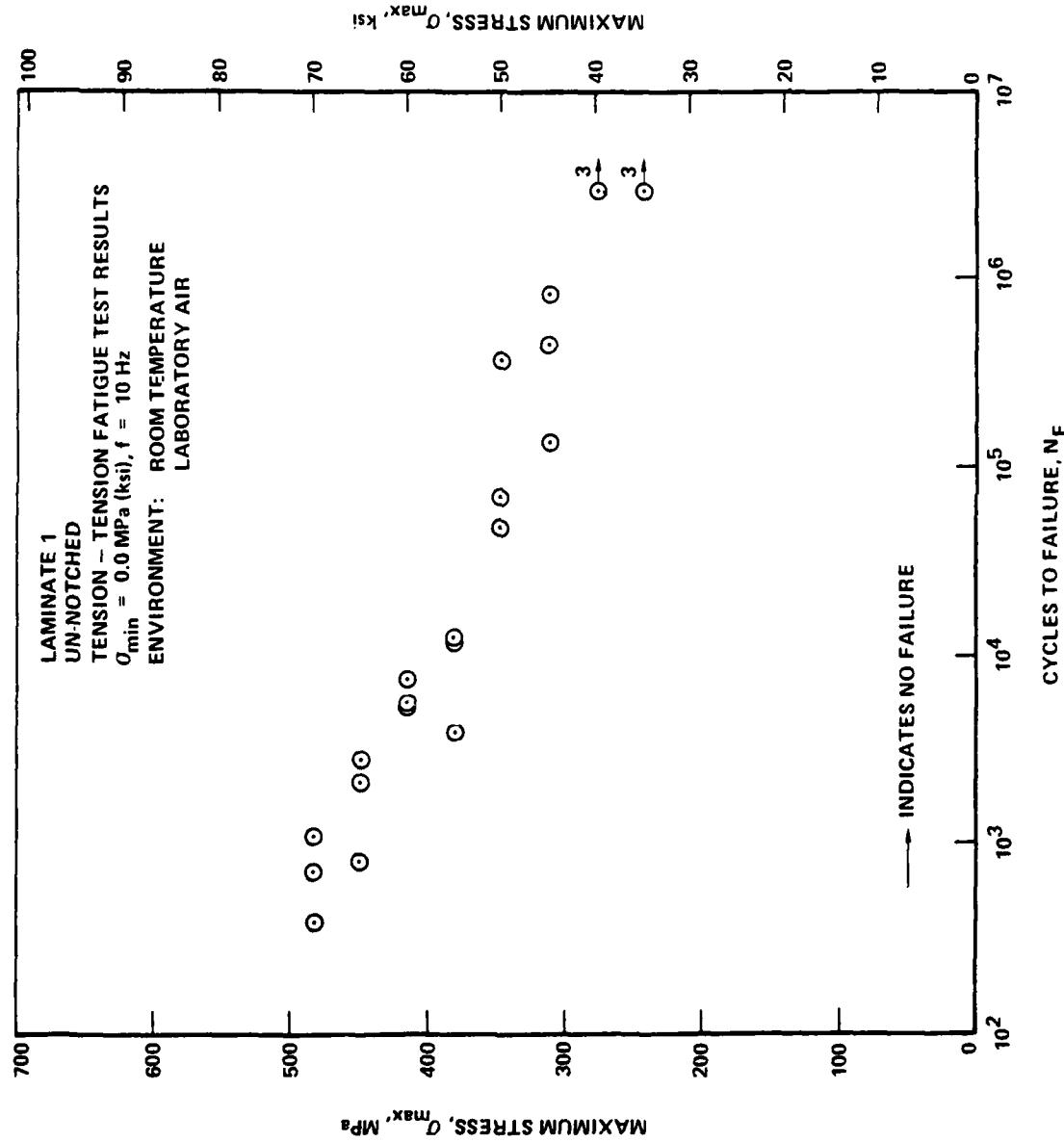
Figure 67. Laminate 1 Un-notched Tension-Tension Fatigue Stress-Life Scan Results at Room Temperature in Laboratory Air

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and 68. For these un-notched coupons, the fatigue behavior was a simple dependence of cycles to failure, N_F, on maximum stress, σ_{max}. This was identical to that found previously [1]. Corresponding S-N scan results for coupons tested at 82.2°C (180°F), 90% R.H., after prior conditioning in the same environment are shown in Figures 69 and 70. These figures show the same simple dependence of cycles to failure, N_F, on maximum stress as observed at room temperature.

Stress-life data for notched laminate 1 coupons, plotted on the basis of un-notched σ_{max}, are shown in Figures 71 to 74. Although the plots are similar to the un-notched data, the tension-tension curve at room temperature is quite flat. This was due to the fact that fatigue induced damage up to and including failure was centered at the holes in the form of small localized delamination regions parallel to the load direction. σ_{max} had to be quite large compared to the static ultimate to significantly propagate these delamination regions under T-T loading. Under T-C loading the delamination regions quickly propagated parallel to the load and expanded transversely. This resulted in the short fatigue lives of notched laminate 1 coupons under T-C loading.

Laminate 2

The un-notched, room temperature, laboratory air, laminate 2 fatigue results were identical to that reported previously [1], see Figures 75 and 76. The S-N curves are extremely flat. None of the coupons exhibited early delamination. At 82.2°C (180°F), 90% R.H., the T-T data was similar to the room temperature data, Figure 77. However, the T-C data does exhibit an S-N curve similar to the laminate 1 data, Figure 78. This is believed to be due to the fact that the high temperature/moisture conditions reduced matrix resistance to out-of-plane bending of the fibers while under the compressive load excursion.

6.2 COMPARISONS OF S-N DATA

Laminate 1

Figures 79 and 80 are a comparison of the results obtained with un-notched laminate 1 coupons fatigue tested in this program from batch SF with those
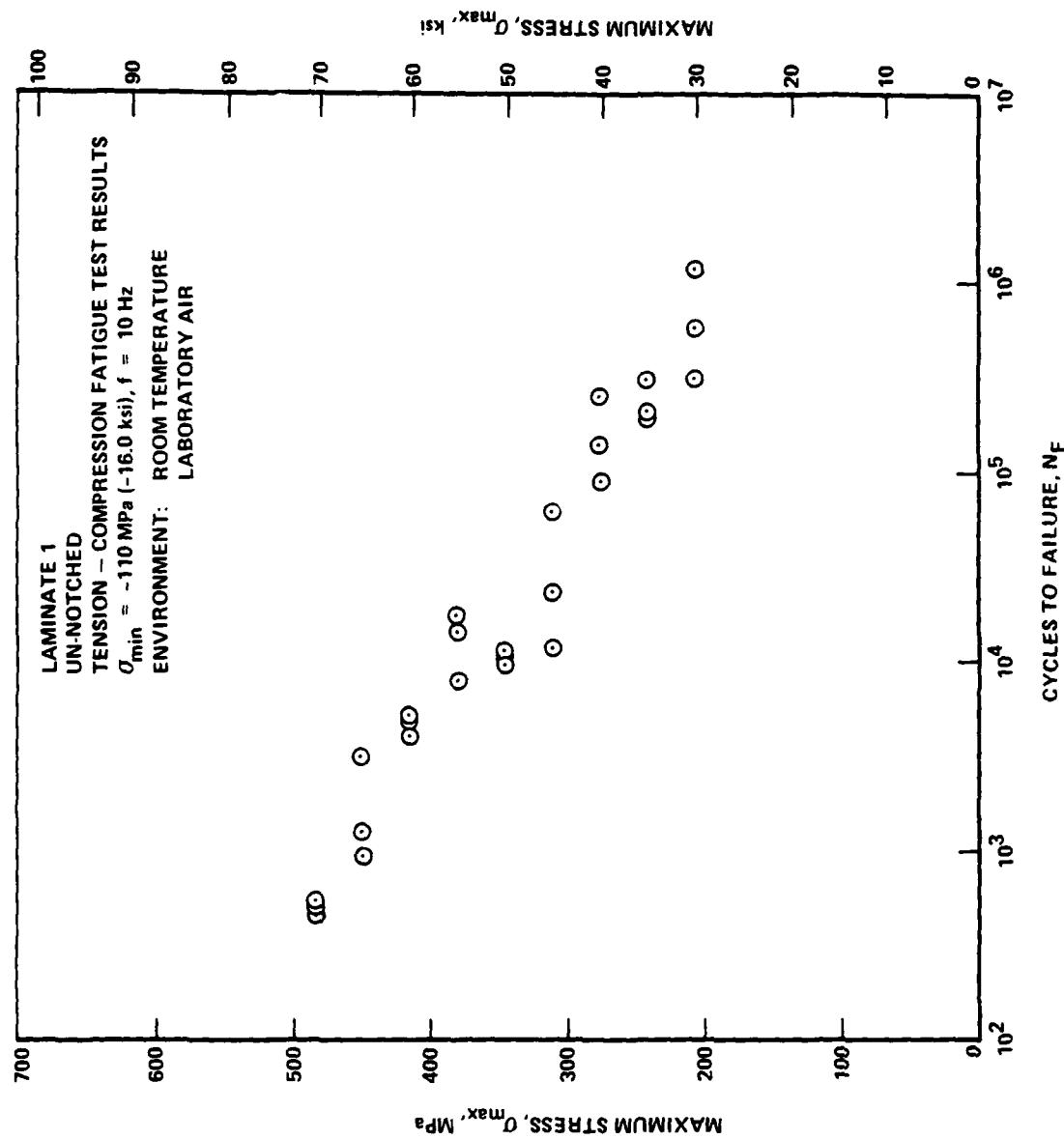
Figure 68. Laminate 1 Un-notched Tension-Compression Fatigue Stress-Life Scan Results at Room Temperature in Laboratory Air

153
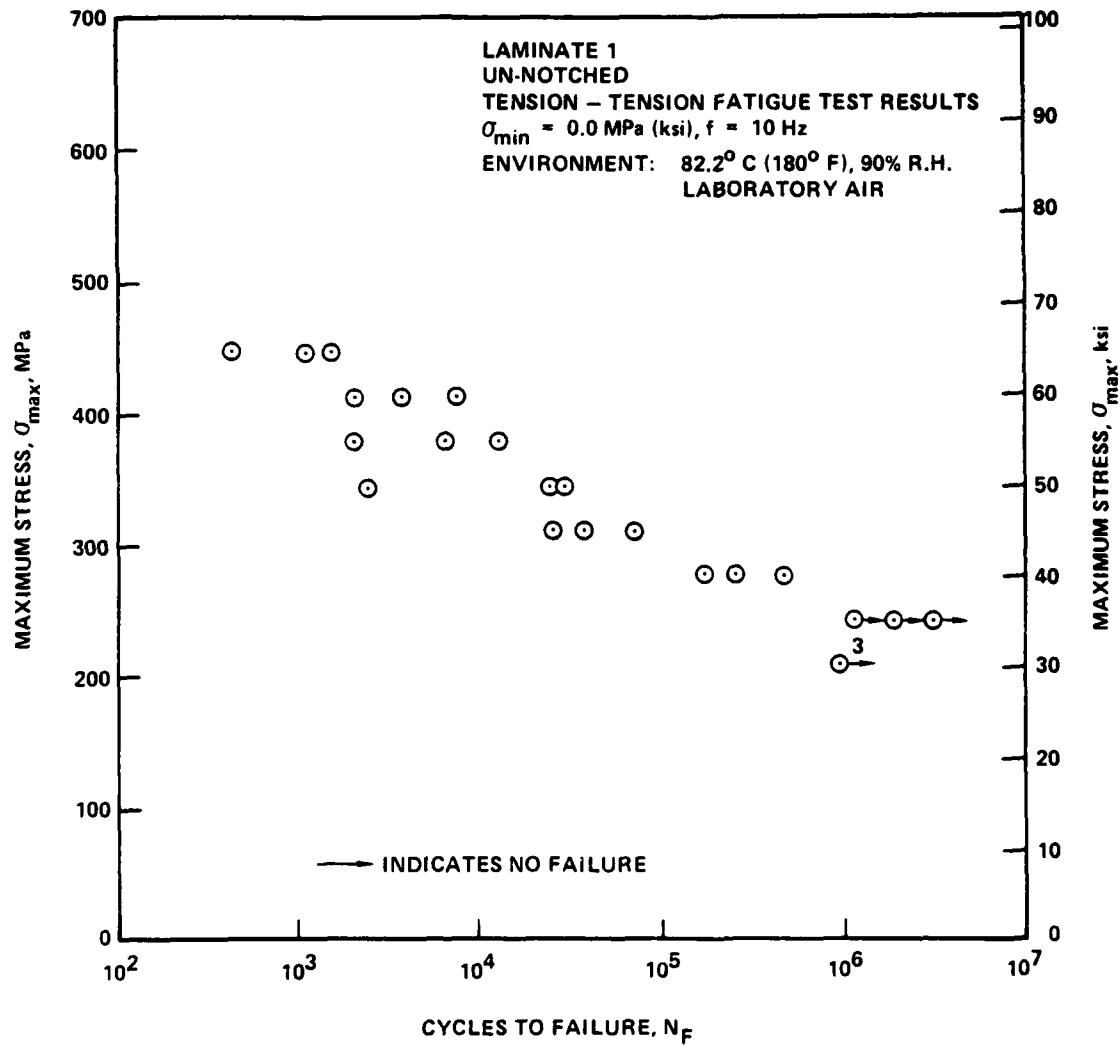
Figure 69.   Laminate 1 Un-notched Tension-Tension Fatigue Stress-Life
             Scan Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air

154
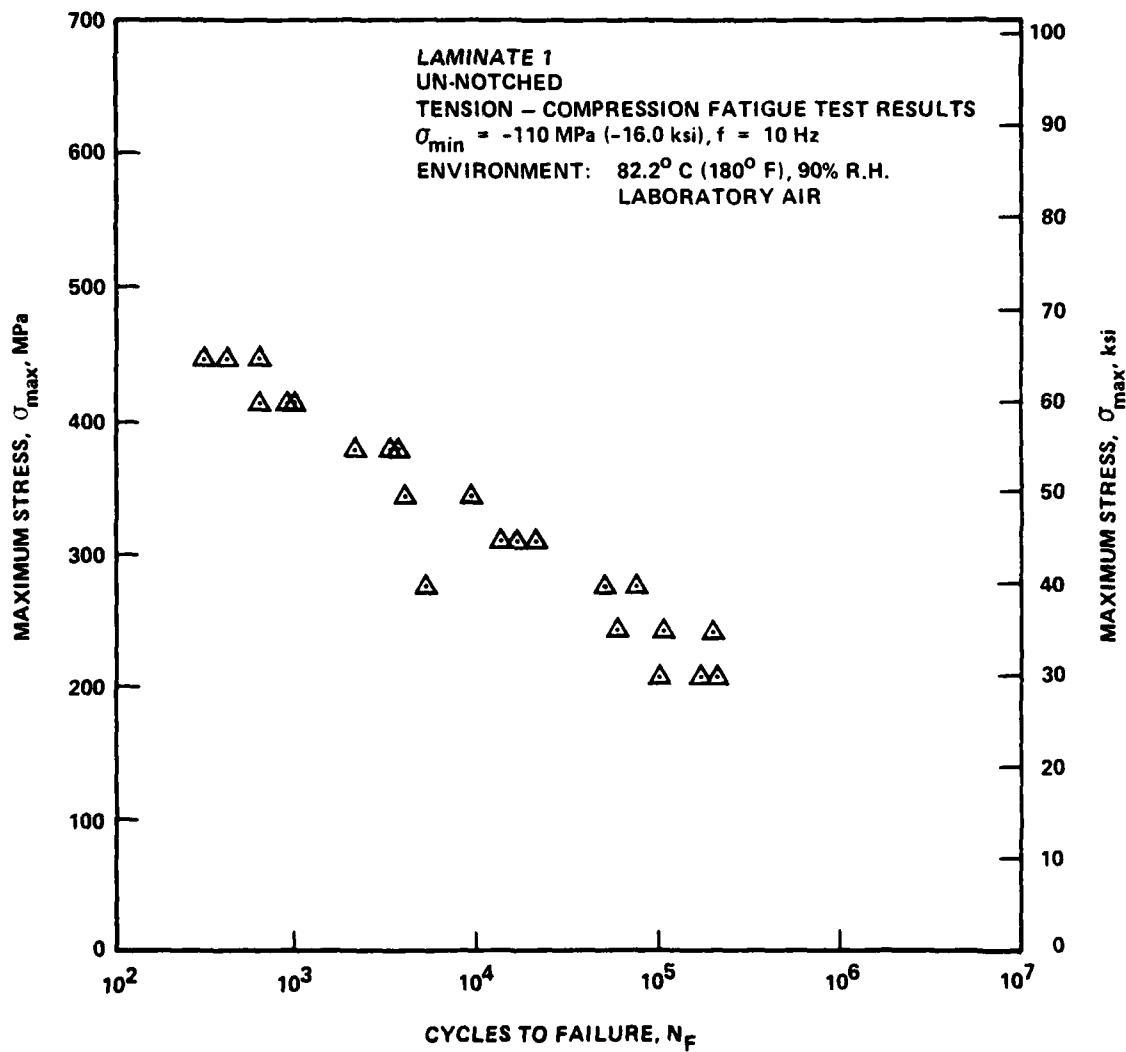
Figure 70.   Laminate 1 Un-notched Tension-Compression Fatigue Stress-Life
             Scan Results at 82.2°C (180°C), at 90% R.H. in Laboratory Air
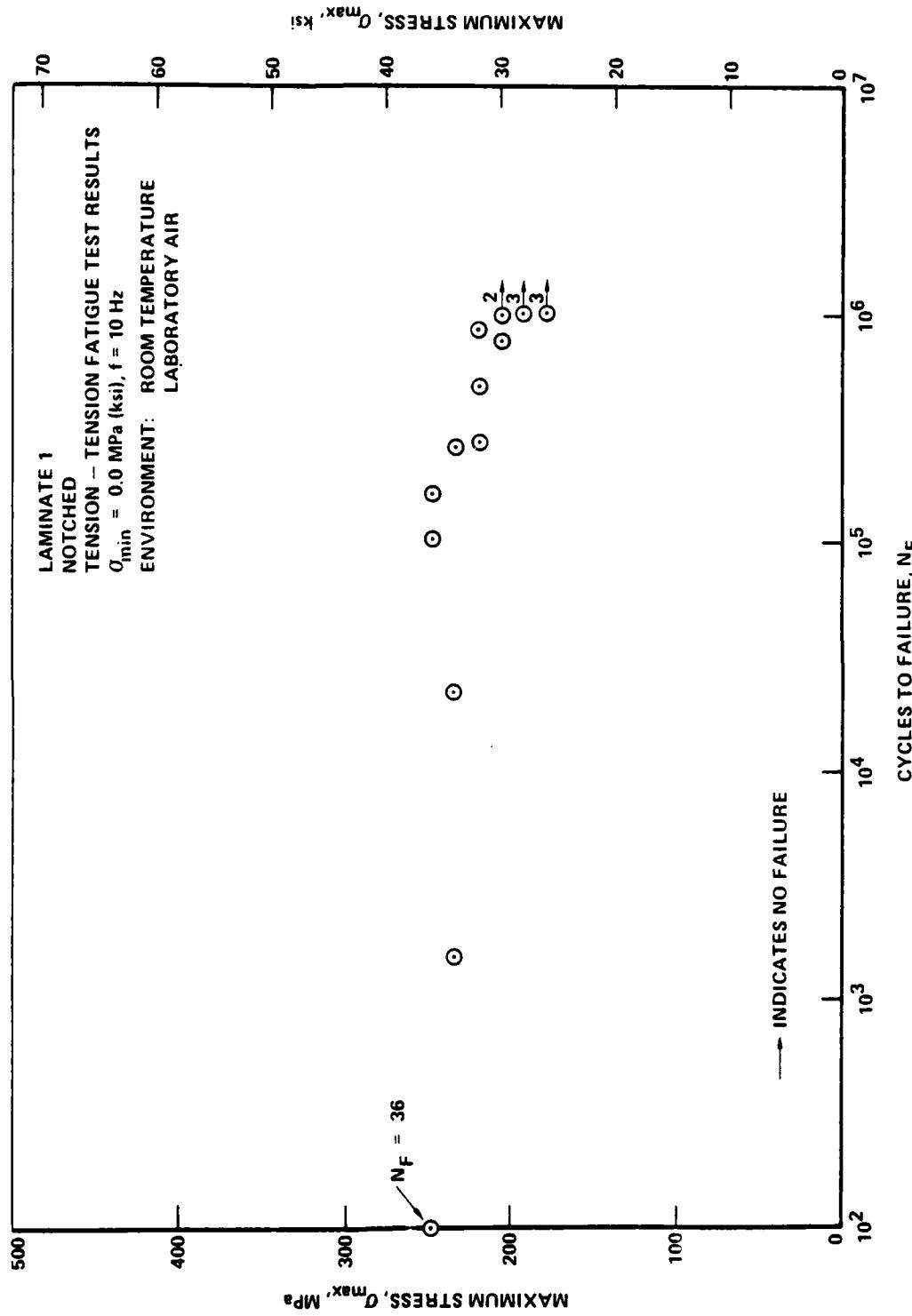
Figure 71. Laminate 1 Notched Tension-Tension Fatigue Stress-Life Results at Room Temperature Laboratory Air

156
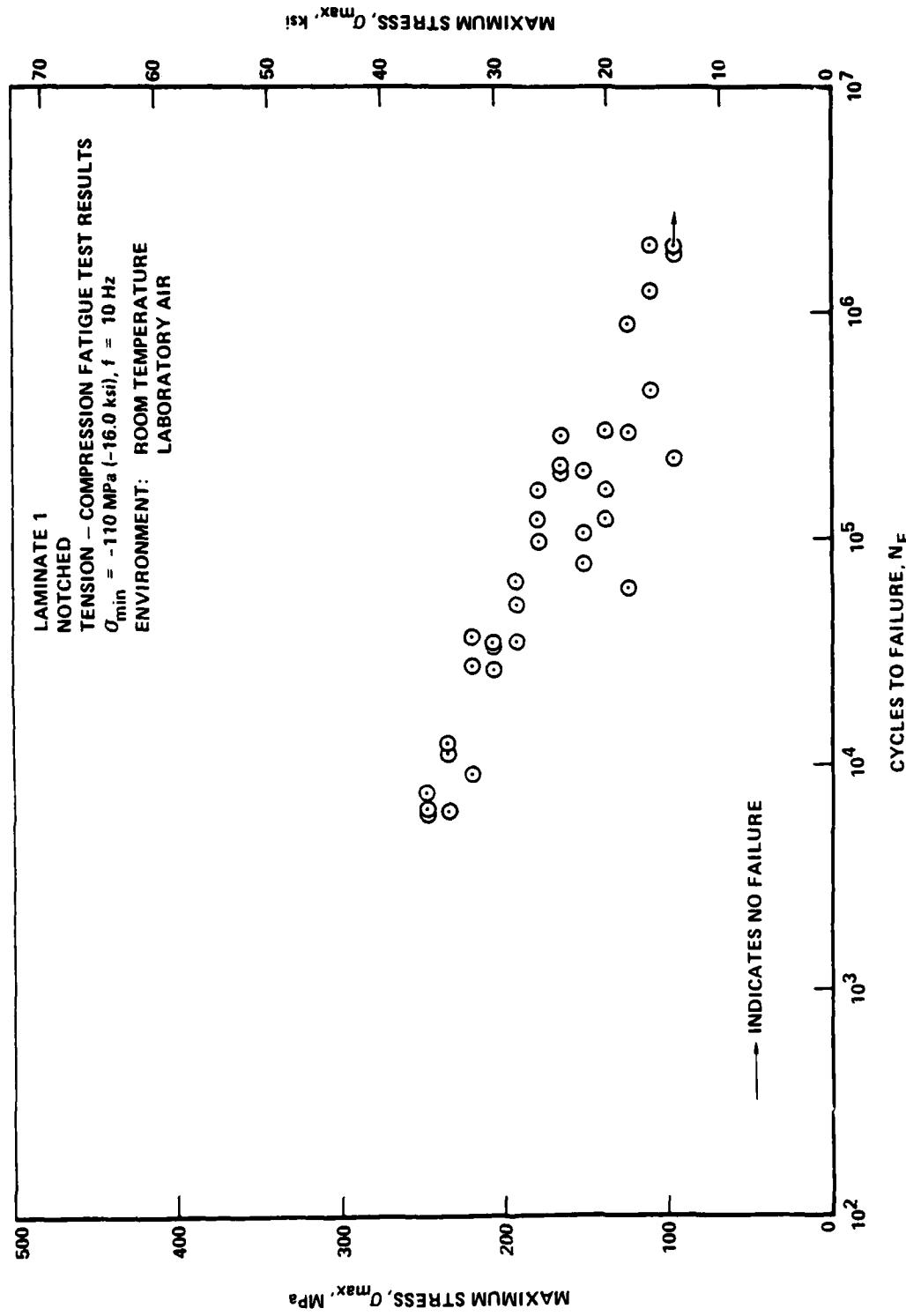
Figure 72. Laminate 1 Notched Tension-Compression Fatigue Stress-Life Results at Room Temperature Laboratory Air

157
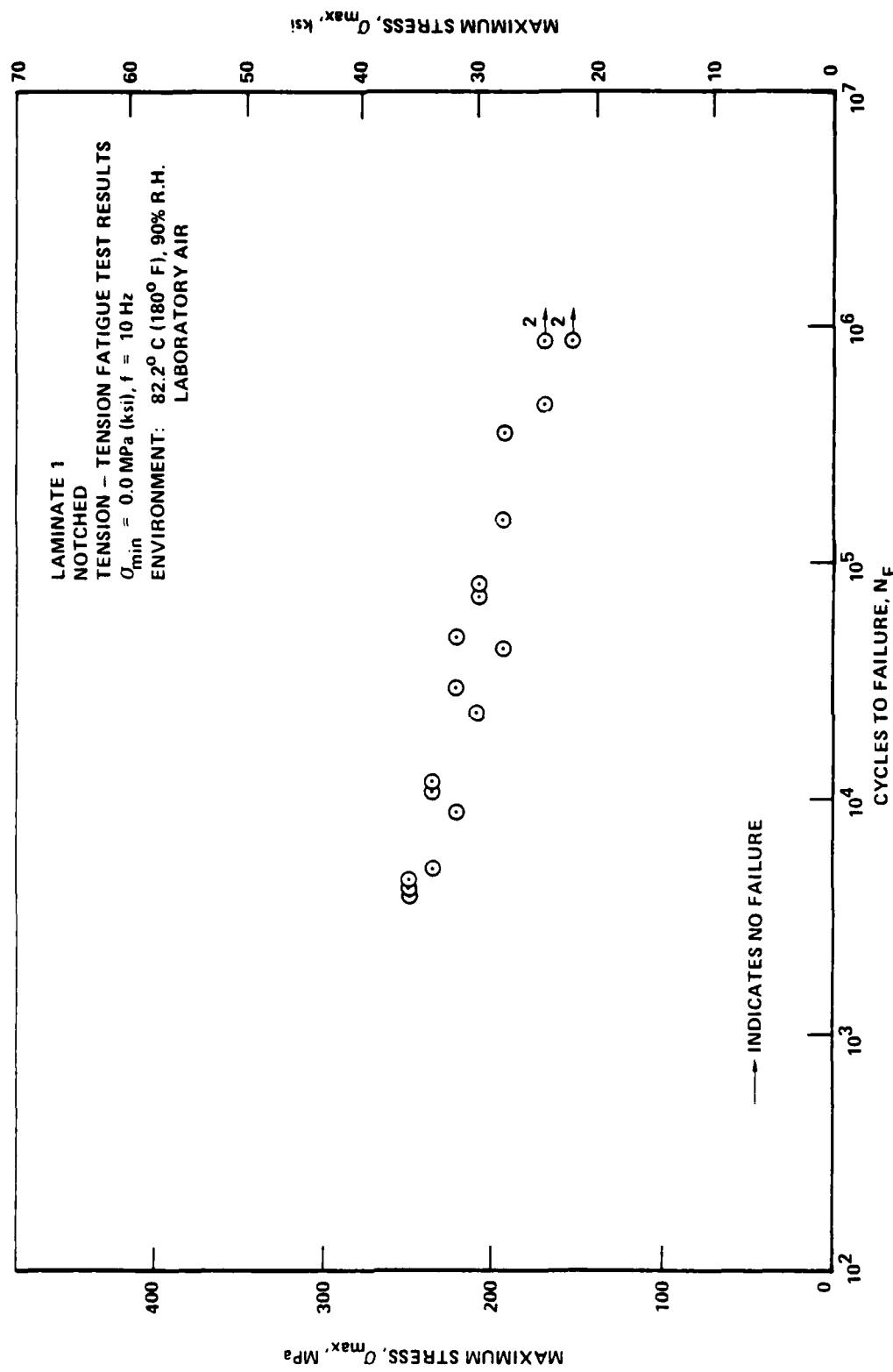
Figure 73. Laminate 1 Notched Tension-Tension Fatigue Stress-Life Scan Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air
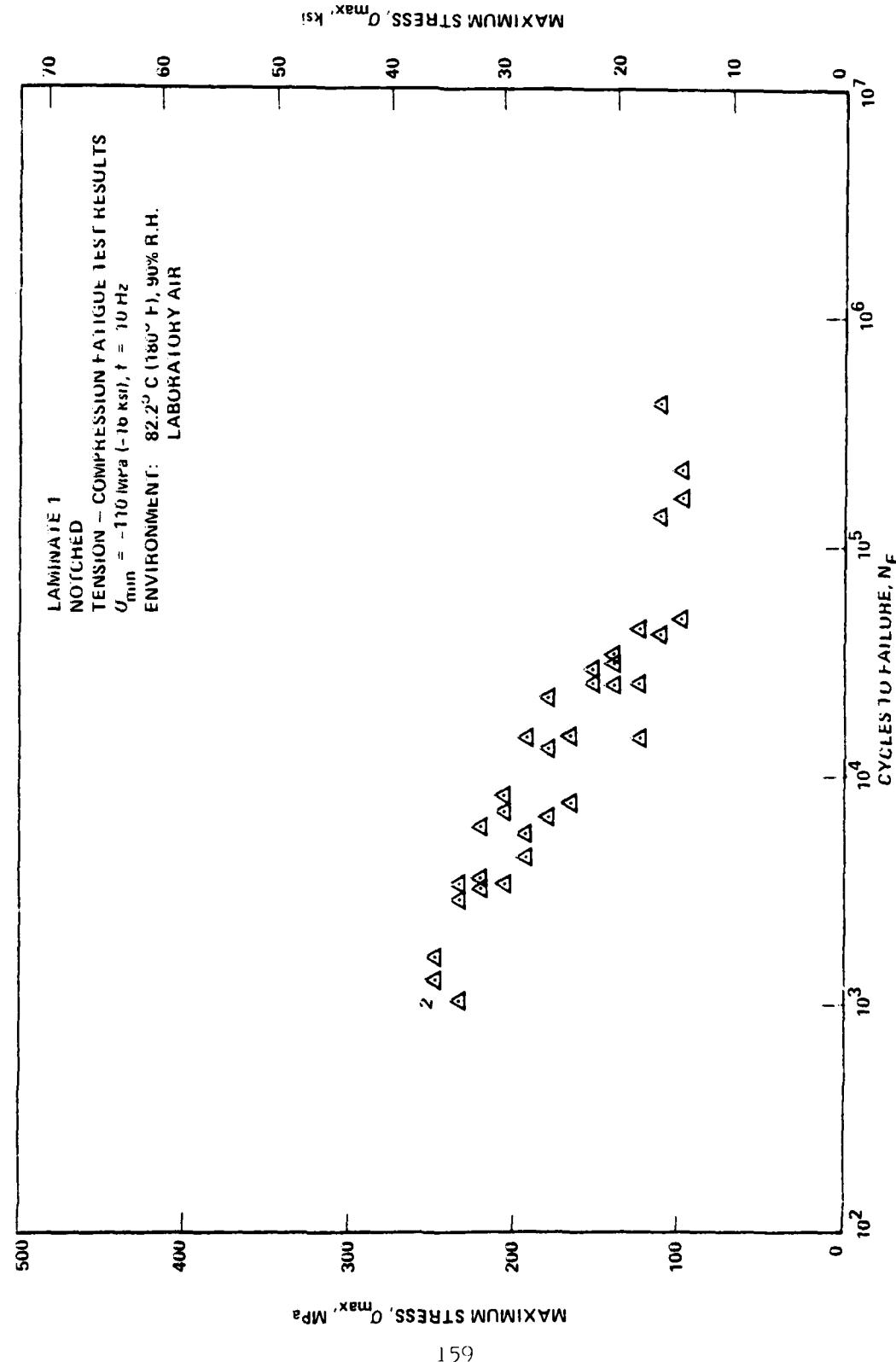
Figure 74. Laminate 1 Notched Tension-Compression Fatigue Stress-Life Scan Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air

159
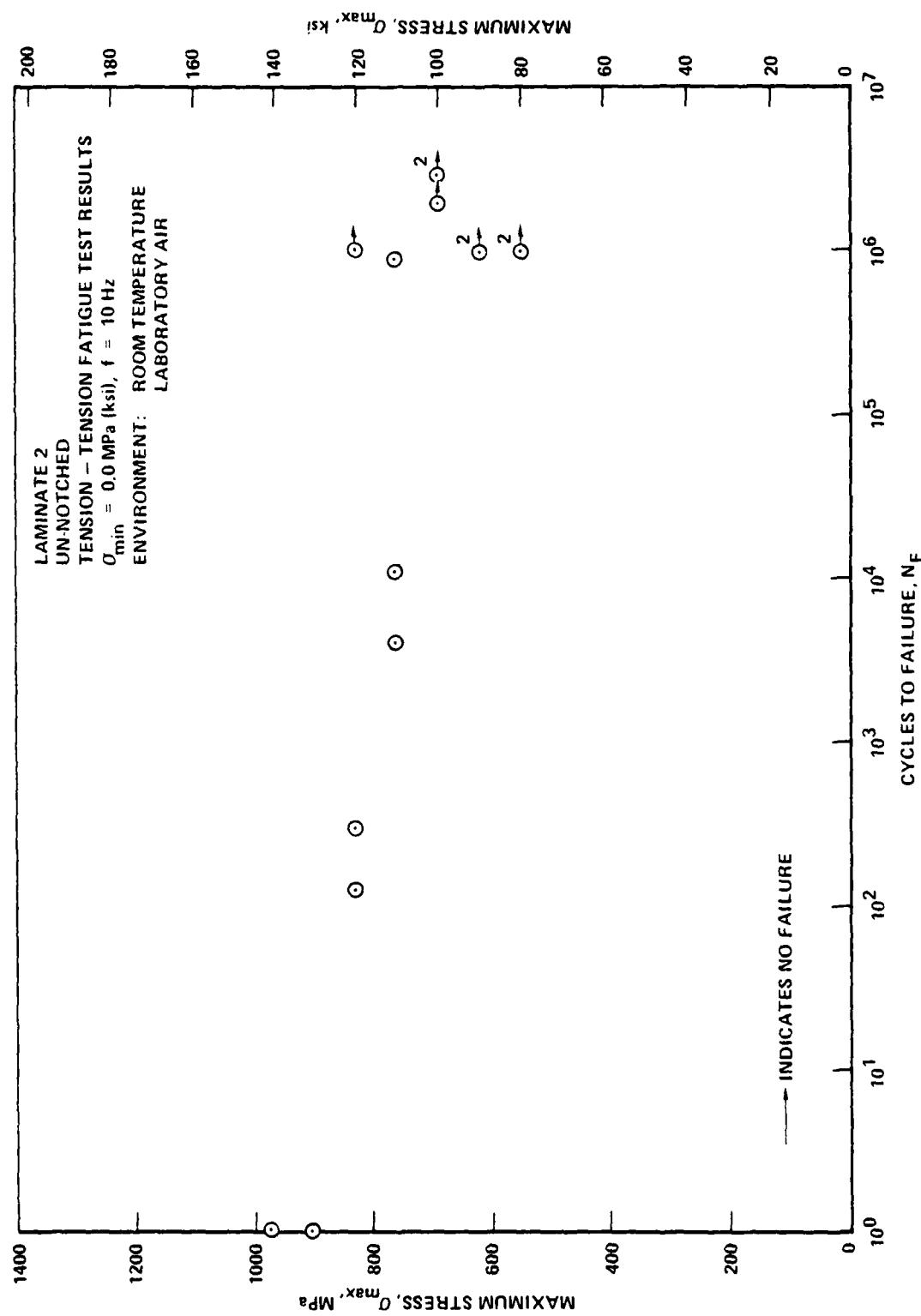
Figure 75. Laminate 2 Un-notched Tension-Tension Fatigue Stress-Life Results at Room Temperature in Laboratory Air
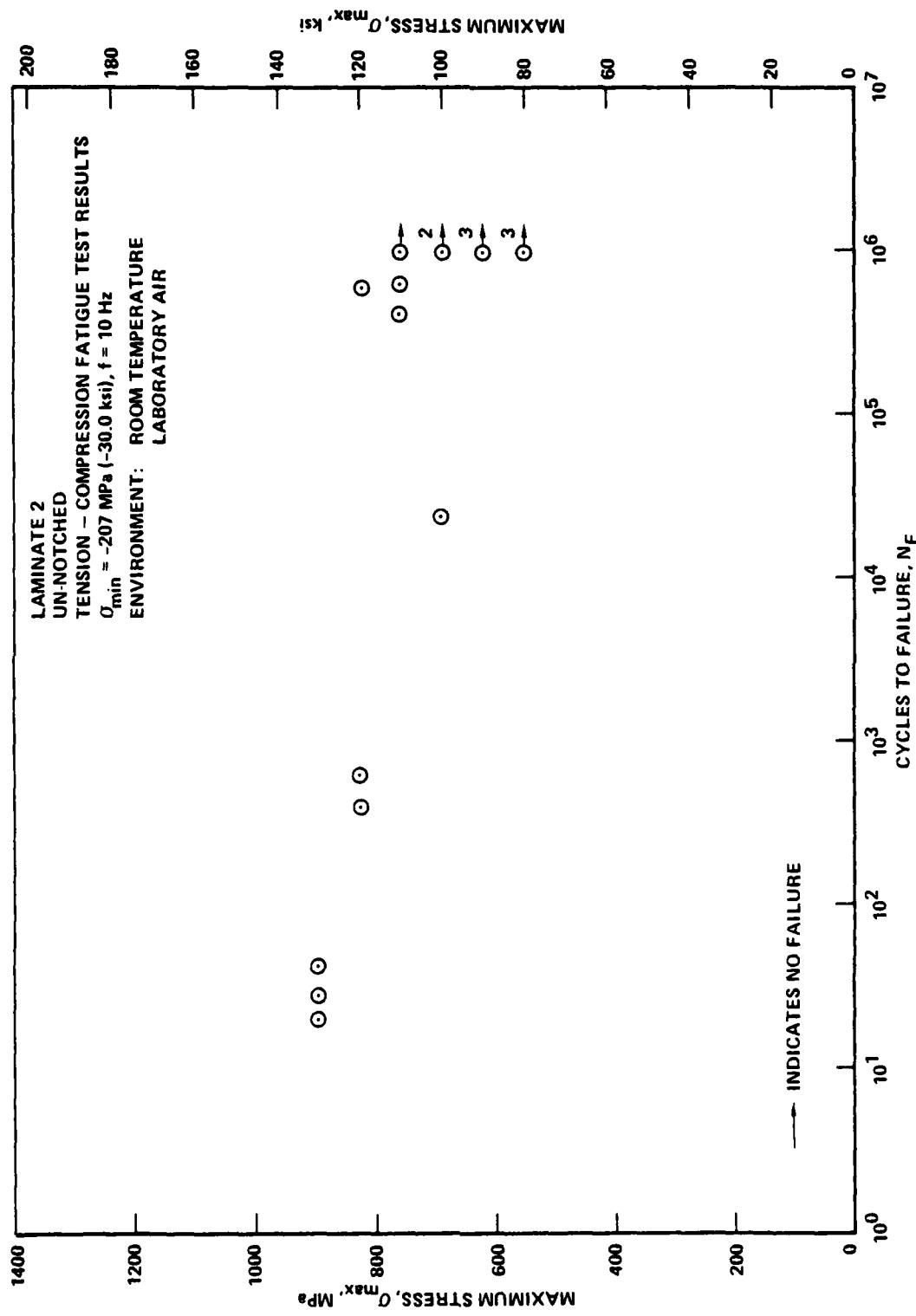
Figure 76. Laminate 2 Un-notched Tension-Compression Fatigue Stress-Life Results at Room Temperature in Laboratory Air
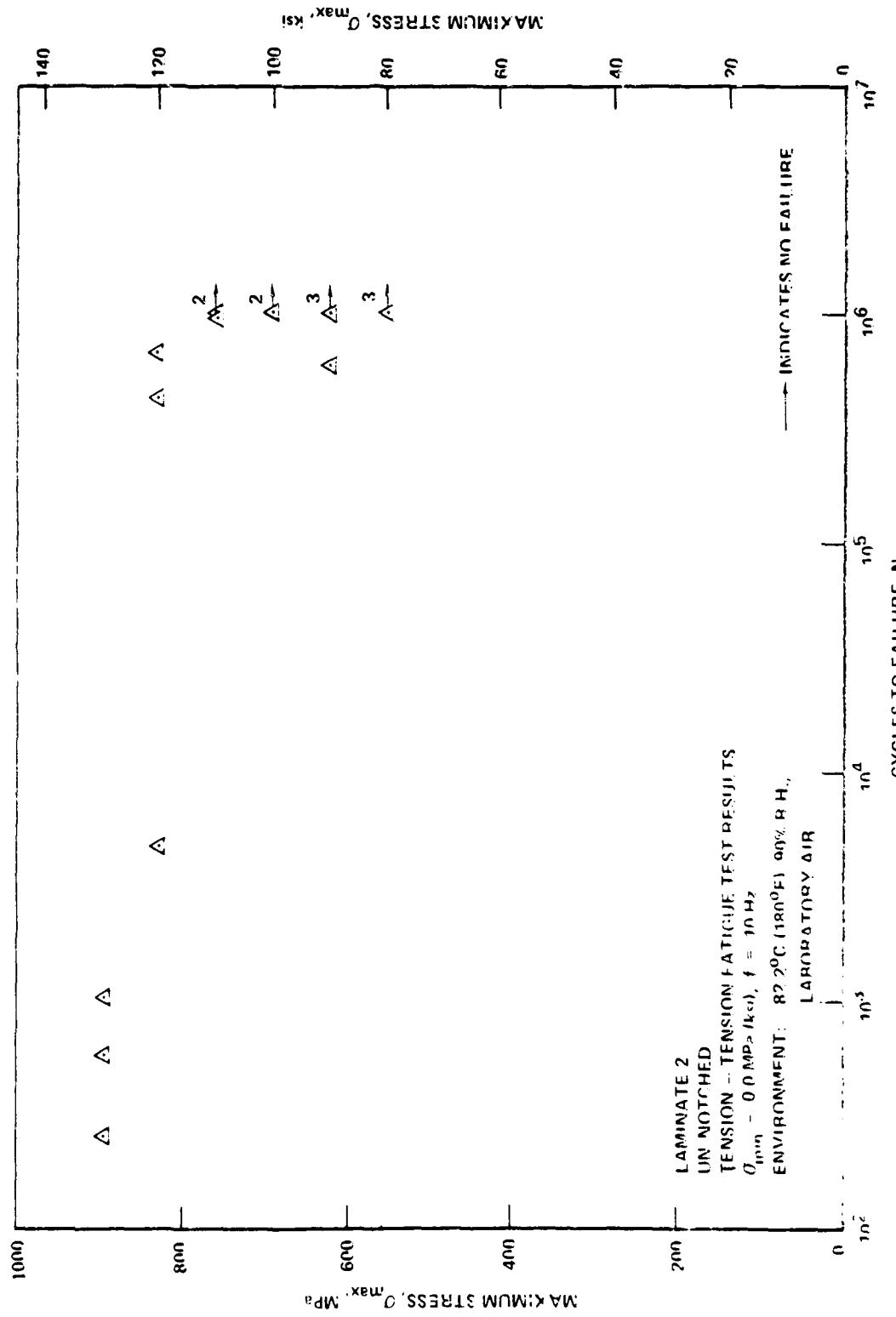
Figure 77. Laminate 2 Un-notched Tension-Tension Fatigue Stress-Life Scan Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air
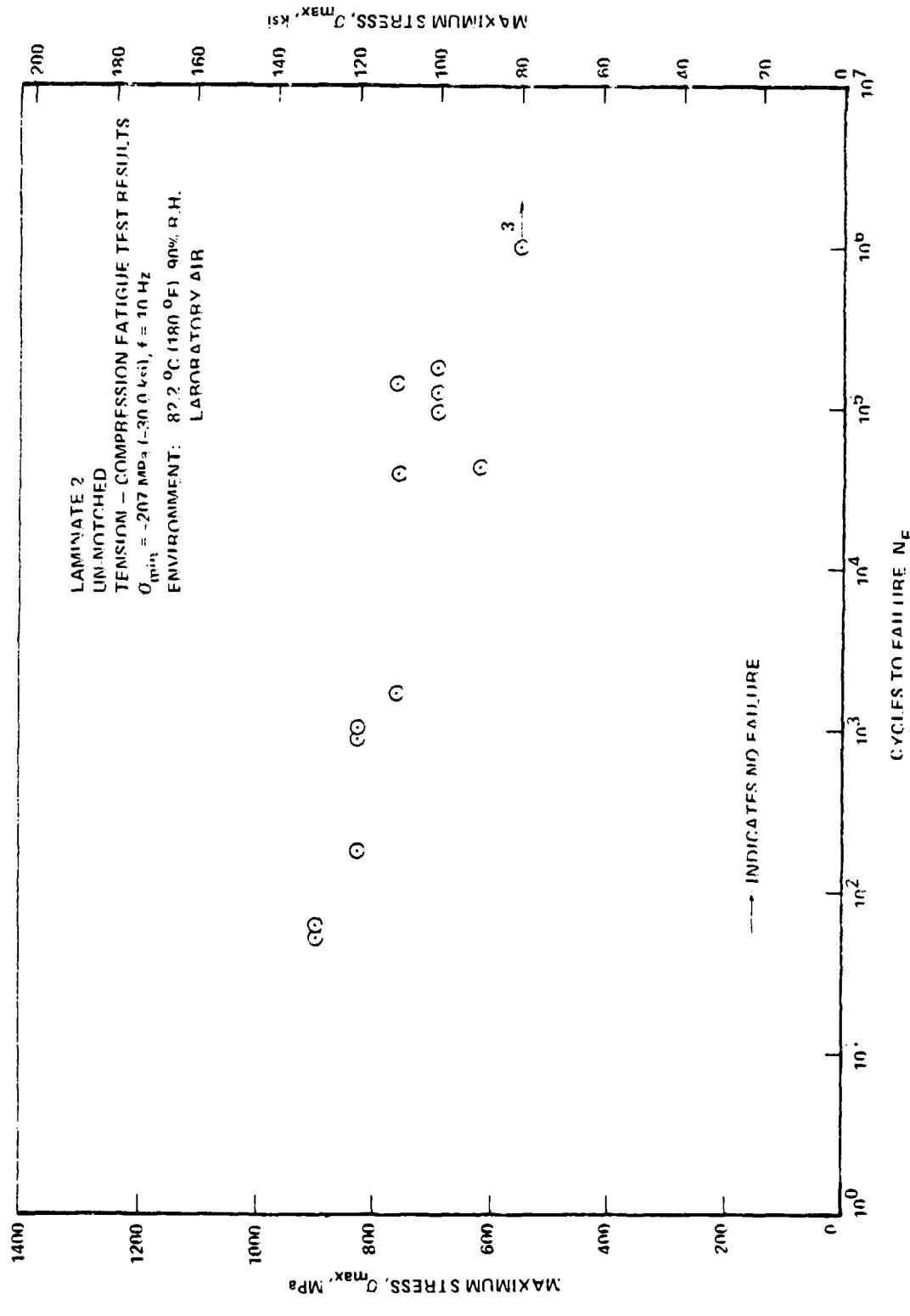
Figure 78. Laminate 2 Un-notched Tension-Compression Fatigue Stress-Life Scan Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air
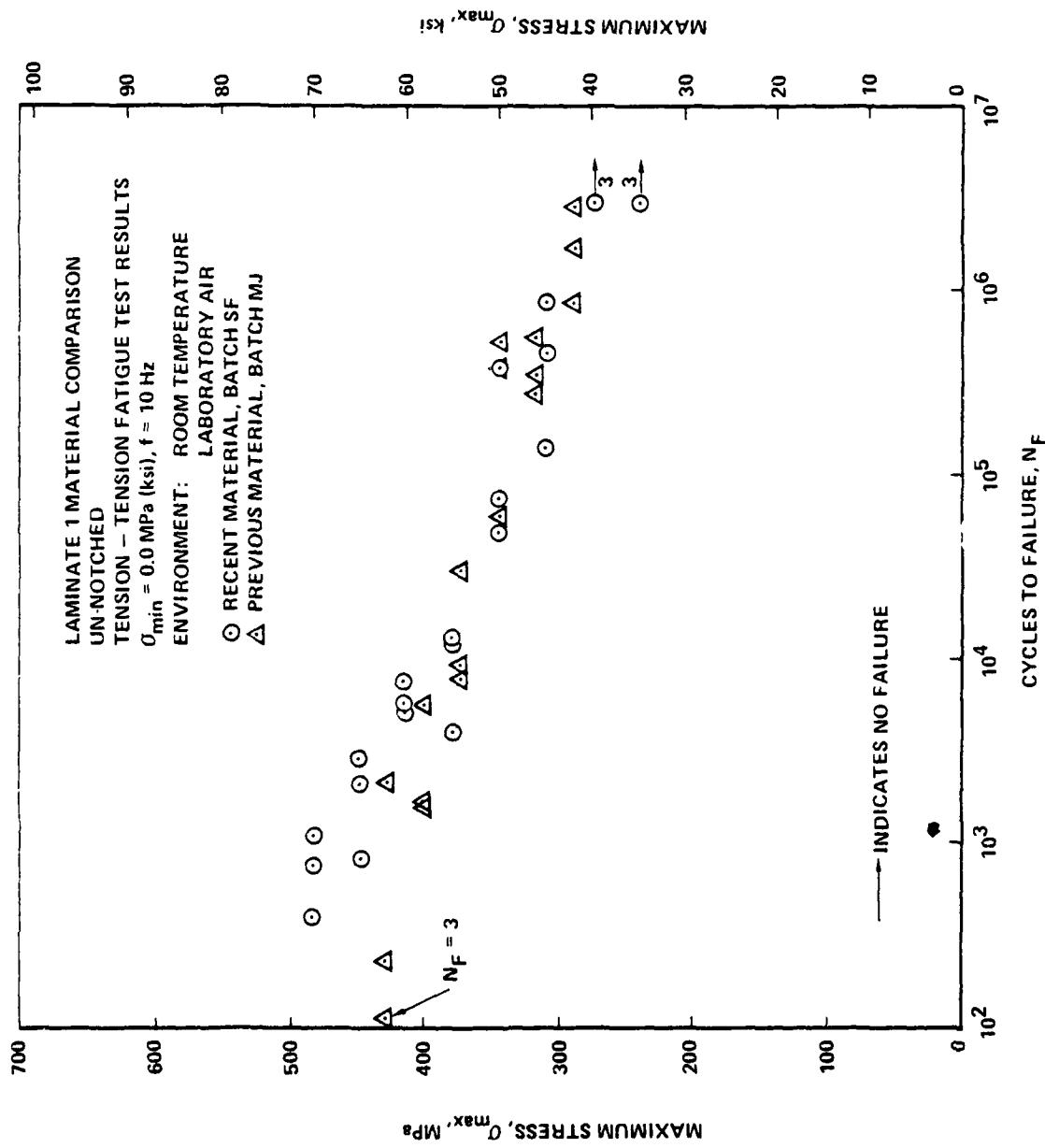
Figure 79. Material Comparison of Laminate 1 Un-notched Coupons Tested Under Tension-Tension Fatigue at Room Temperature in Laboratory Air

164
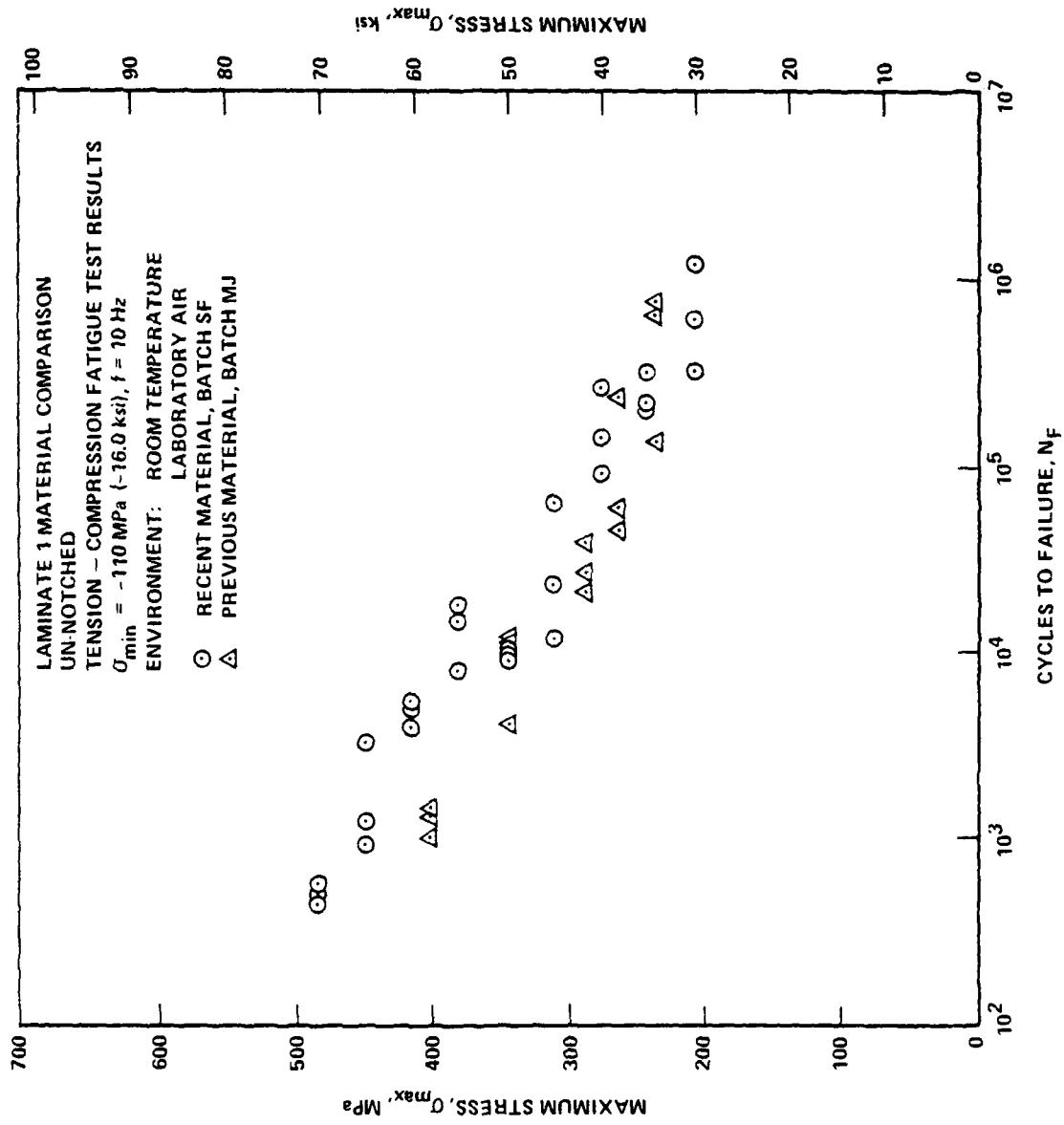
Figure 80. Material Comparison of Laminate 1 Un-notched Coupons Tested Under Tension-Compression Fatigue at Room Temperature in Laboratory Air

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tested in the previous program [1] from batch MJ. At higher stress levels, the fatigue lives for the new batch SF are longer than those for batch MJ due to the higher tensile strength of batch SF. At lower stress levels, the two curves essentially converged.

Similar to previous data [1], the unnotched T-T and T-C data merged at higher σ_{max} levels and diverged at lower levels. This was true at room temperature, Figure 81, or high temperature, Figure 82. In both environments, the compression loading reduced the fatigue life; this was also the result for the notched data, Figures 83 and 84. The effect of the notch on the fatigue life is displayed in Figures 85 to 38. At room temperature, the notched T-T curve is quite unlike the unnotched, Figure 85, but this was less true at high temperature, Figure 87.

The effect of the 82.2°C (180°F), 90% R.H. environment was compared to the room temperature, laboratory air environment, Figures 89 to 92. The effect of the high temperature and humidity environment was to decrease the fatigue lives by approximately a factor of 3 for the unnotched coupons and by 10 for the notched coupons. For the notched coupons under T-T loading, Figure 91, the fatigue curve changed from being relatively flat to the more usually observed S-N curve.

Laminate 2

The unnotched laminate 2 S-N fatigue results are compared in Figures 93 to 96. The effect of environment is difficult to discern because of the flatness and large scatter of the curves. However, an effect of the high temperature/moisture conditioning is evident in the tension-compression results, Figures 94 and 96. Under T-C fatigue loading at high temperature, no run-outs at 10^6 cycles occurred above 550 MPa (80 ksi) in contrast to the room temperature data where run-outs occurred at 759 MPa (110 ksi).
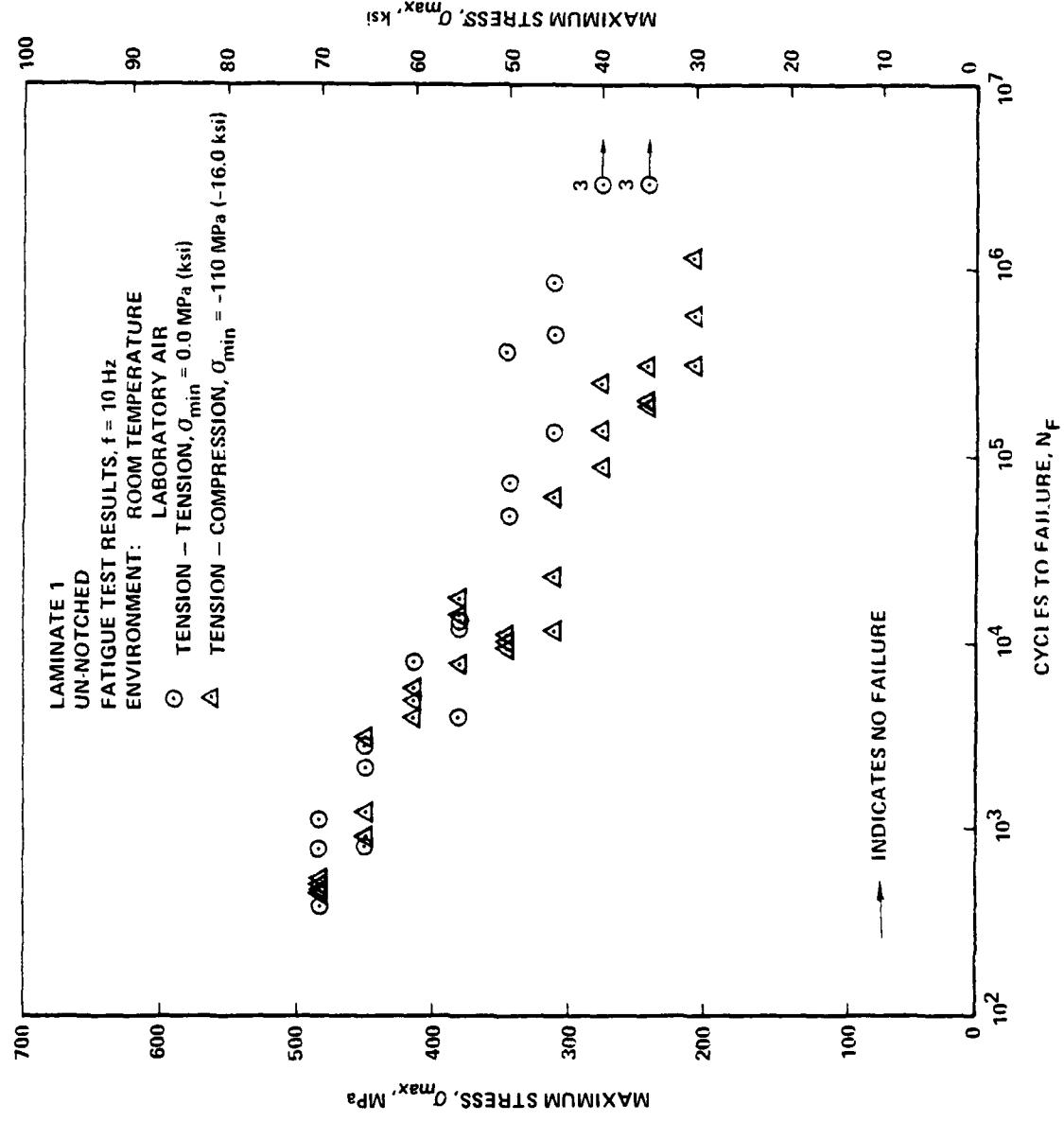
Figure 81. Comparison of Laminate 1 Un-notched Tension-Tension and Tension-Compression Fatigue Stress-Life Results at Room Temperature in Laboratory Air

167
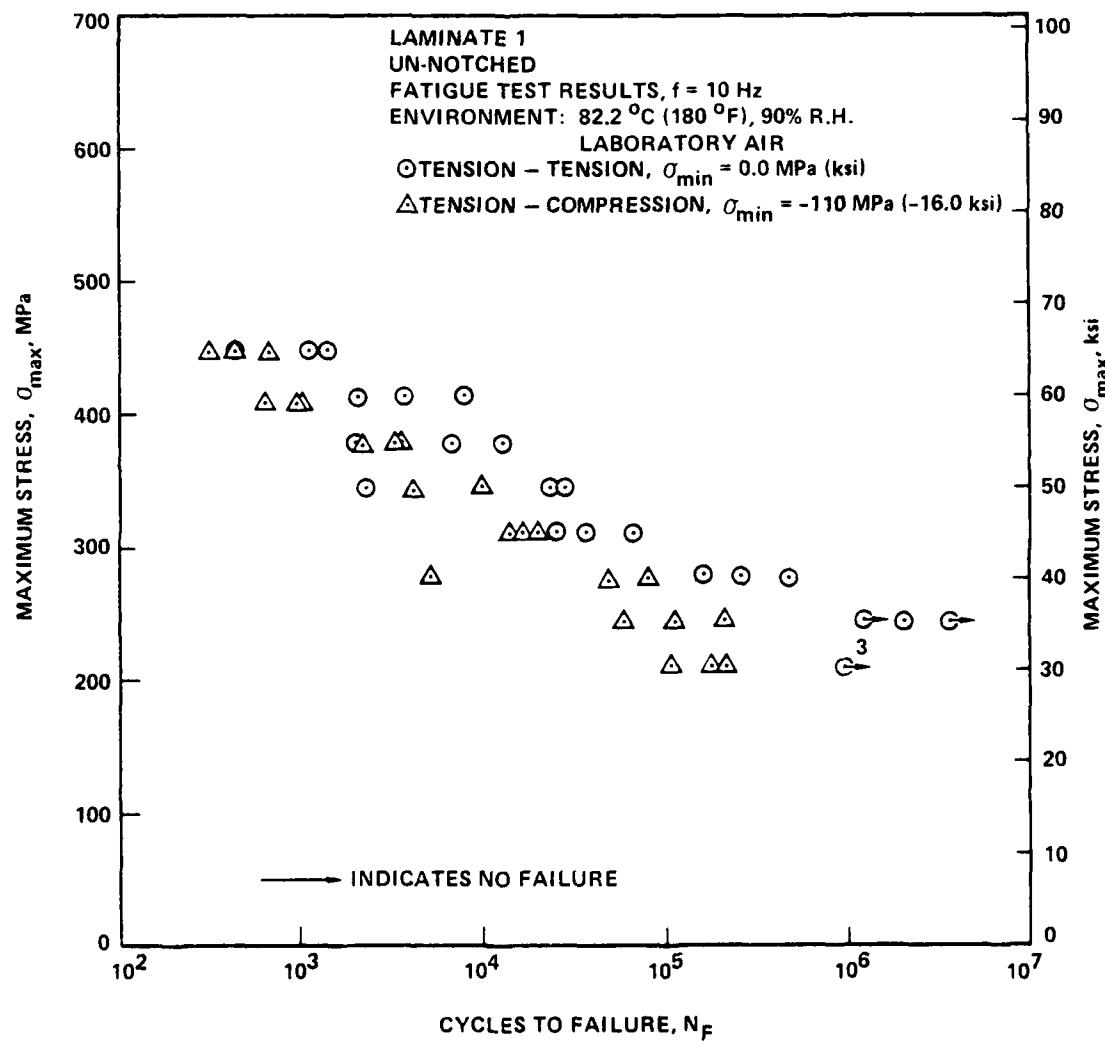
Figure 82. Comparison of Un-notched Tension-Tension and Tension-Compression Fatigue Stress-Life Results at 82.2°C (180°F) at 90% R.H.

168
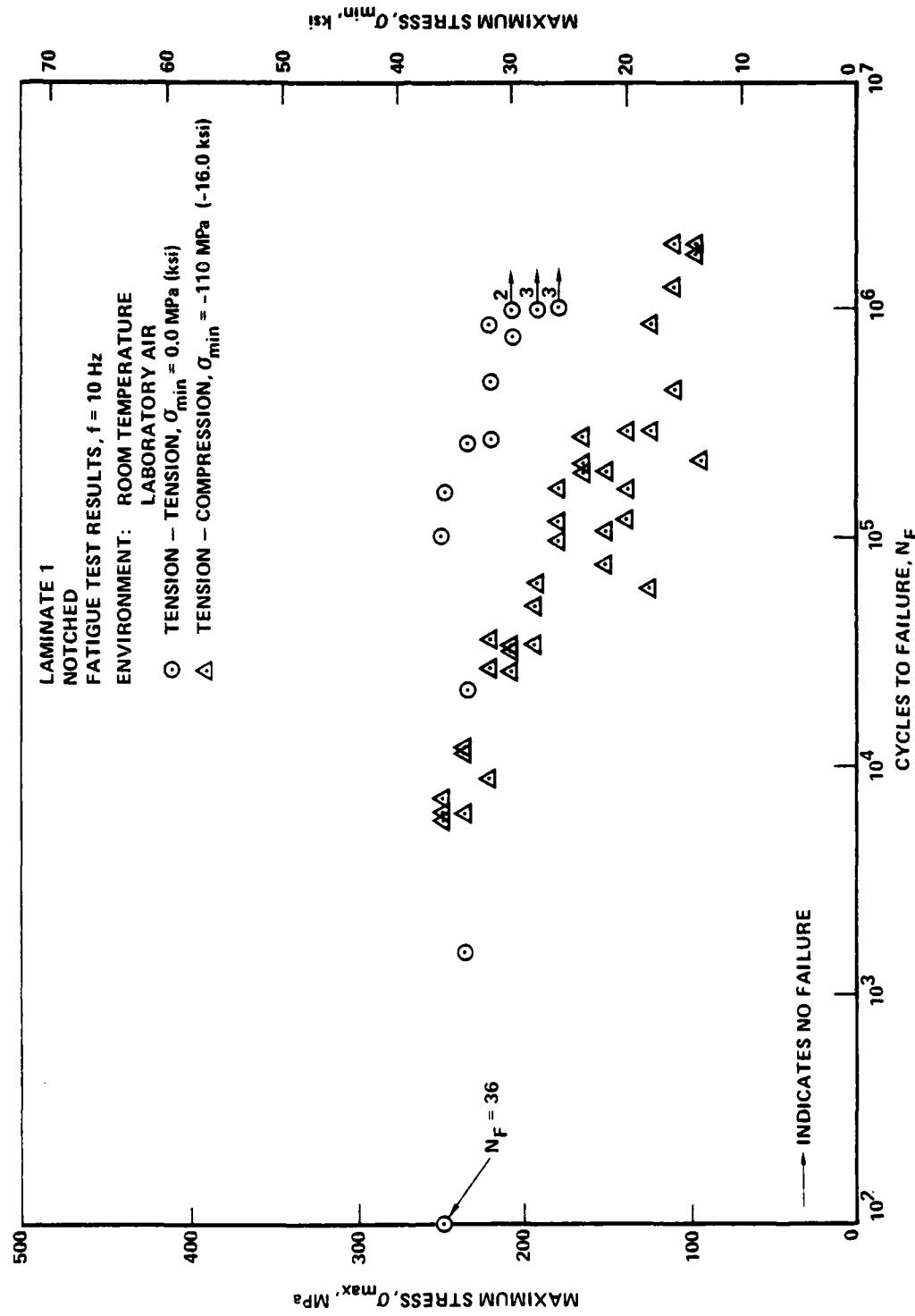
Figure 83. Comparison of Laminate 1 Notched Tension-Tension and Tension-Compression Fatigue Stress-Life Results at Room Temperature in Laboratory Air

169
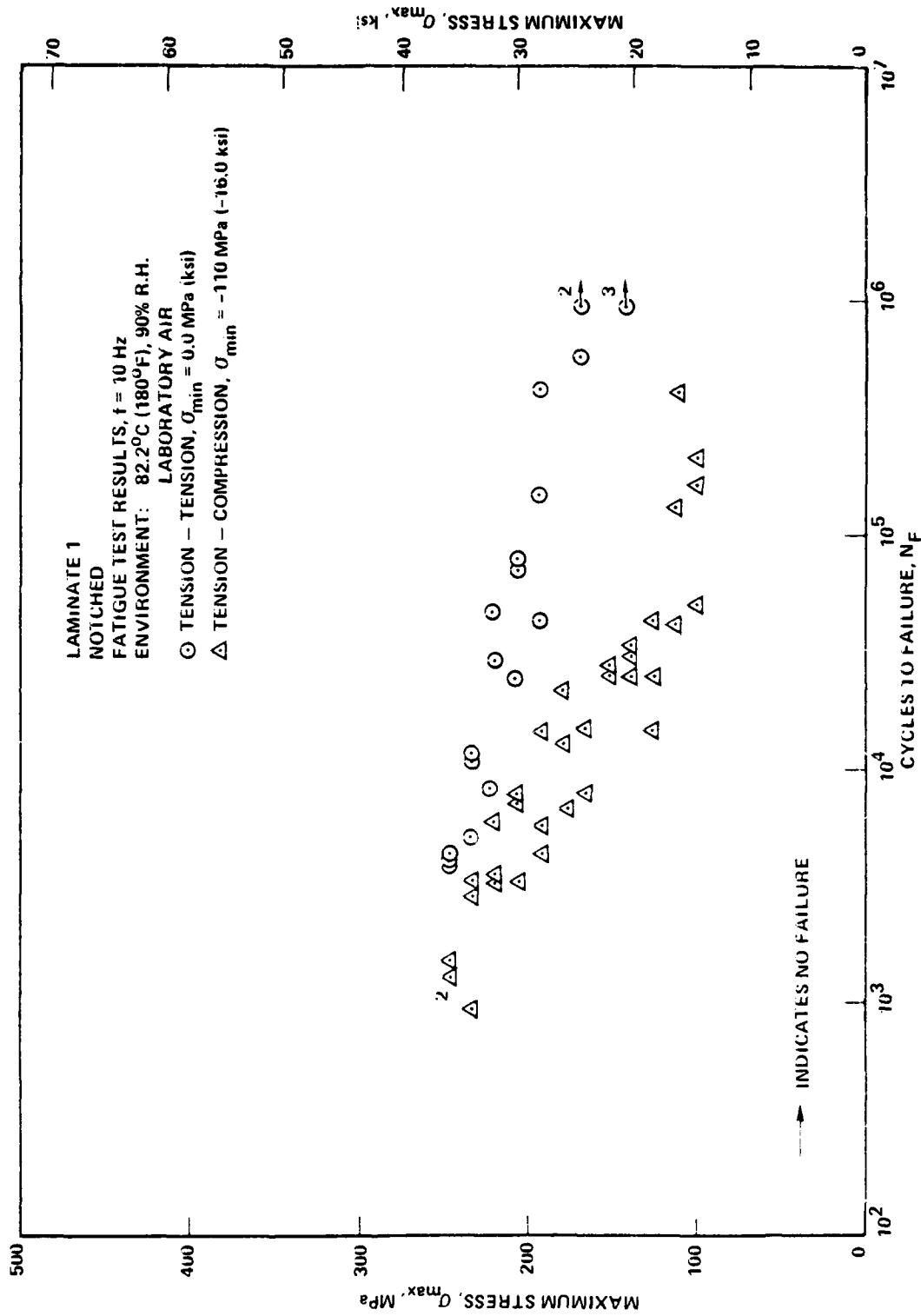
Figure 84. Comparison of Laminate 1 Notched Tension-Tension and Tension-Compression Fatigue Stress-Life Results at 82.2°C (180°F) at 90% R.H.
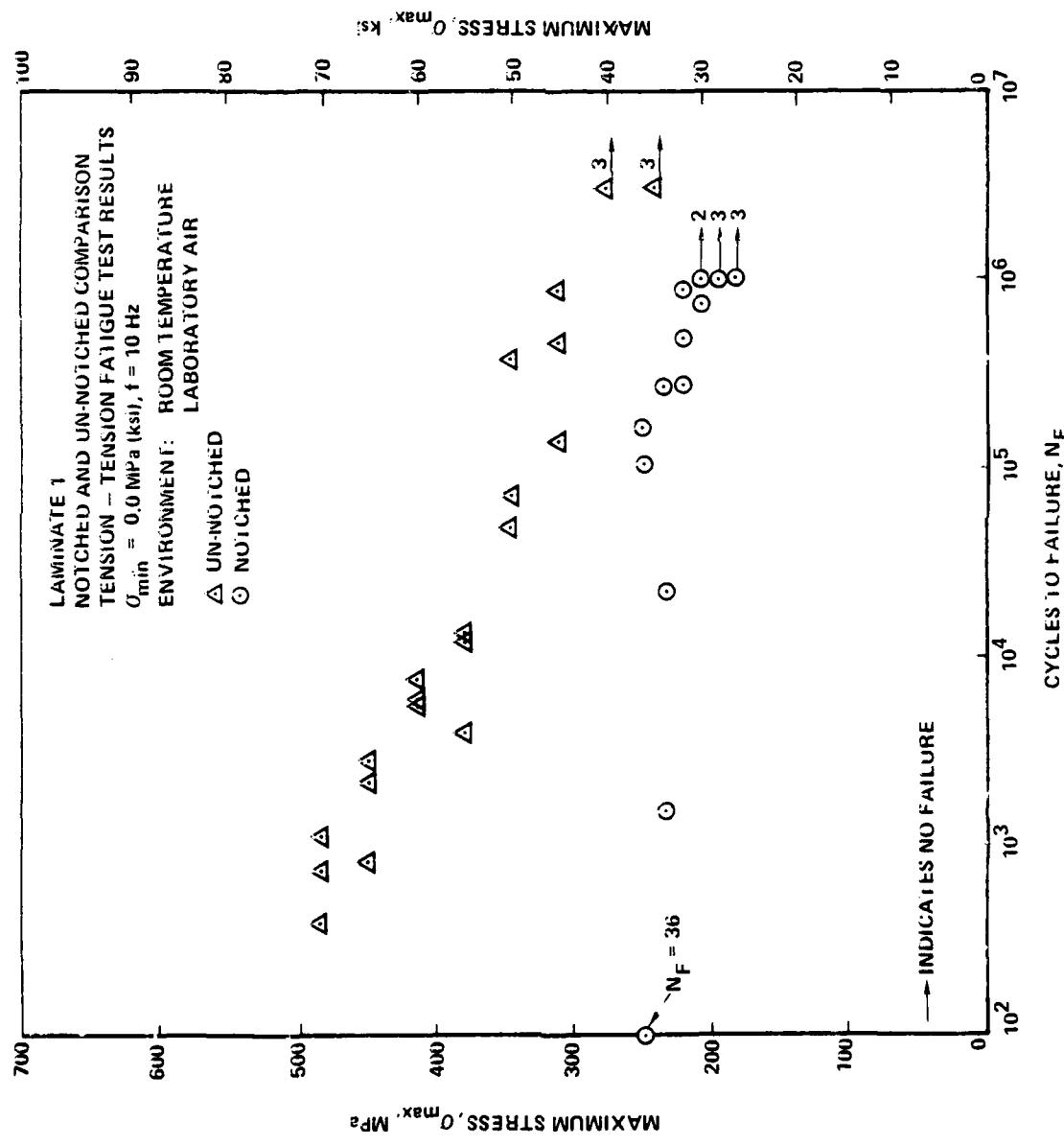
Figure 85. Comparison of Laminate 1 Notched and Un-notched Tension-Tension
Fatigue Stress-Life Results at Room Temperature in Laboratory Air

171
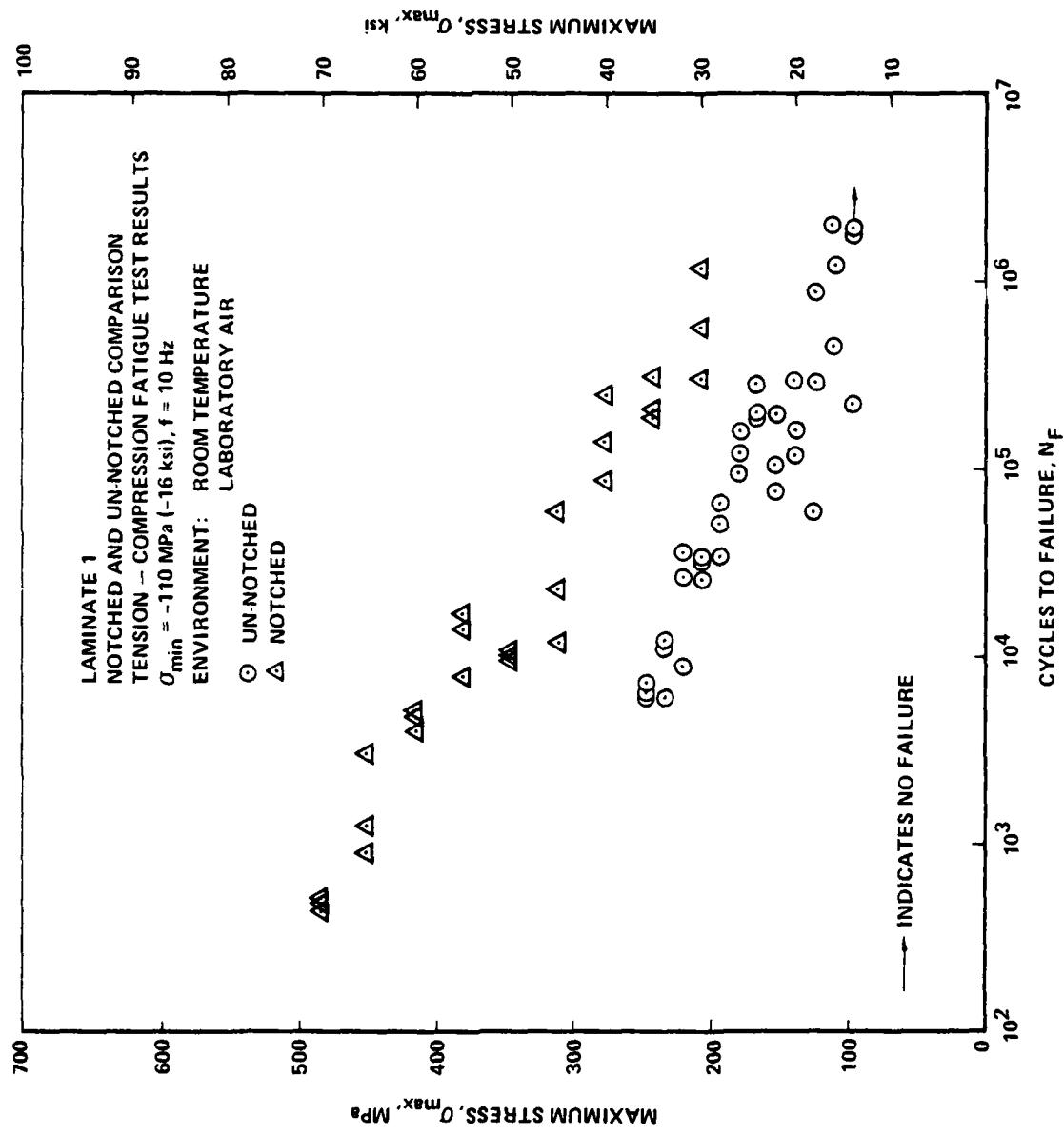
Figure 86. Comparison of Laminate 1 Notched and Un-notched Tension-Compression Fatigue Stress-Life Results at Room Temperature in Laboratory Air

172
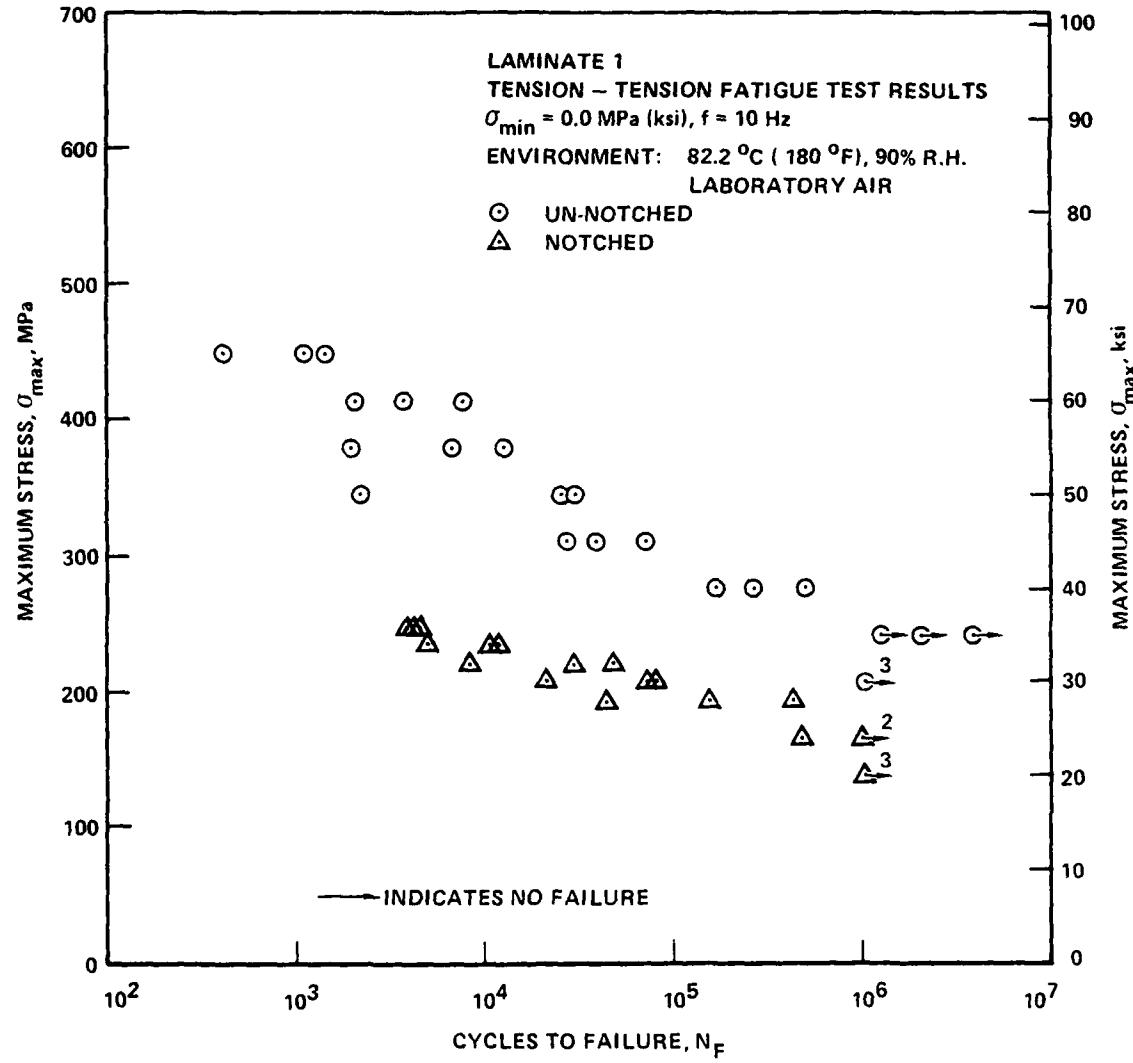
Figure 87. Comparison of Laminate 1 Notched and Un-notched Tension-Tension Fatigue Stress-Life Results at 82.2°C (180°F), 90% R.H., in Laboratory Air

173
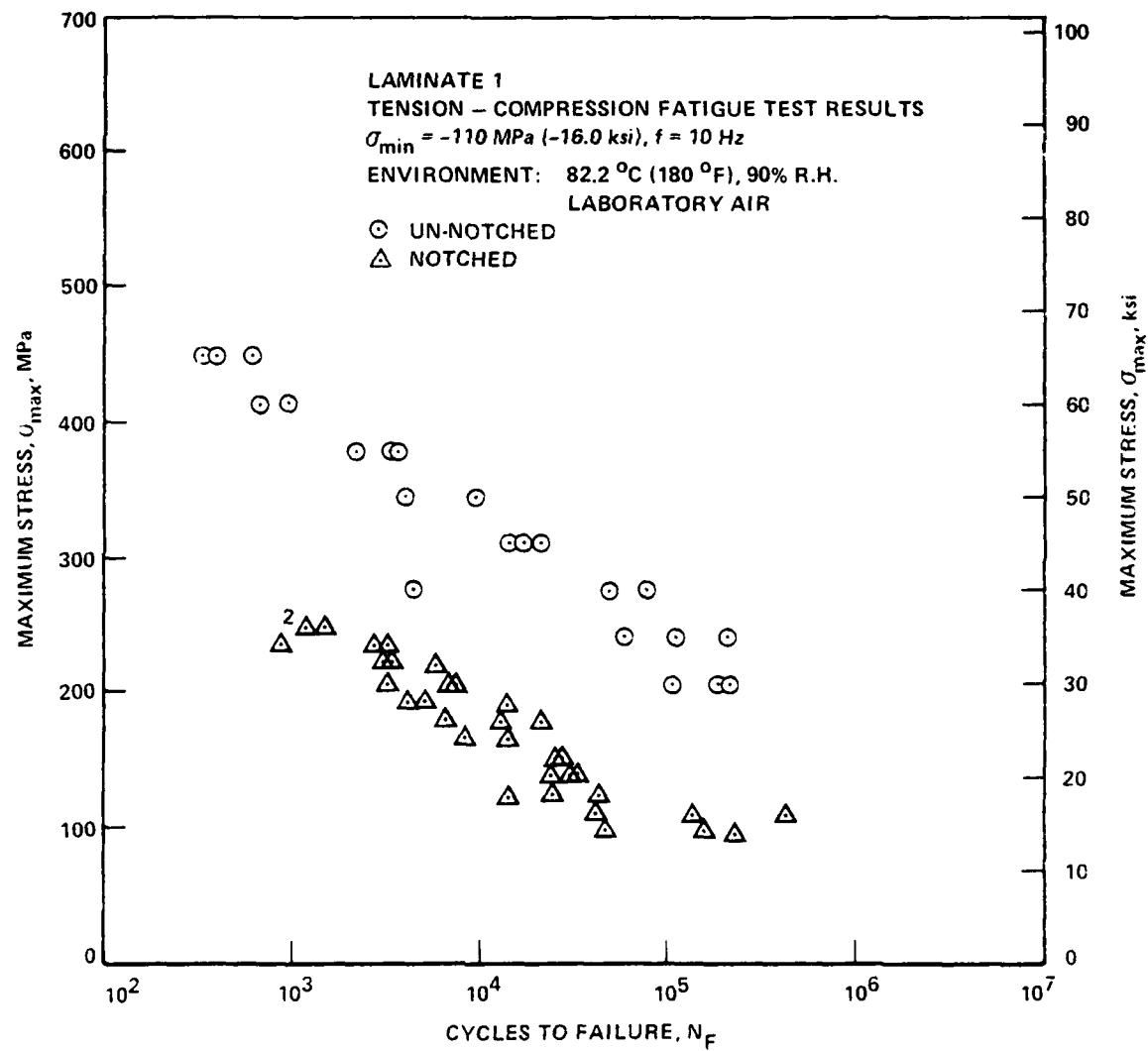
Figure 89. Comparison of Laminate 1 Notched and Un-notched Tension-Compression Fatigue Stress-Life Results at 82.2°C (180°F) 90% R.H. in Laboratory Air

Figure 89. Comparison of Laminate 1 Un-notched Tension-Tension Fatigue Stress-Life Results at Room Temperature and 82.2°C (180°F), 90% R.H.

175
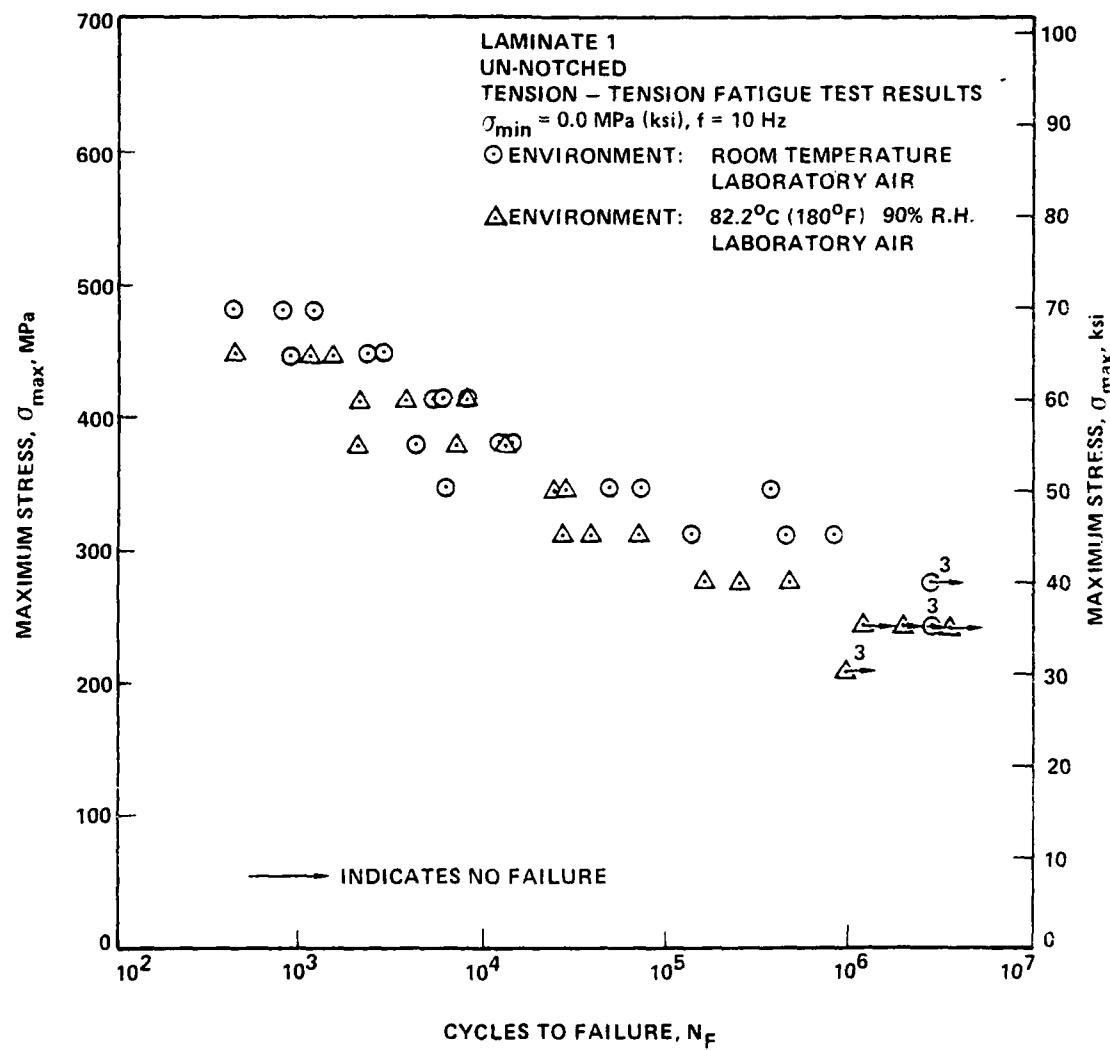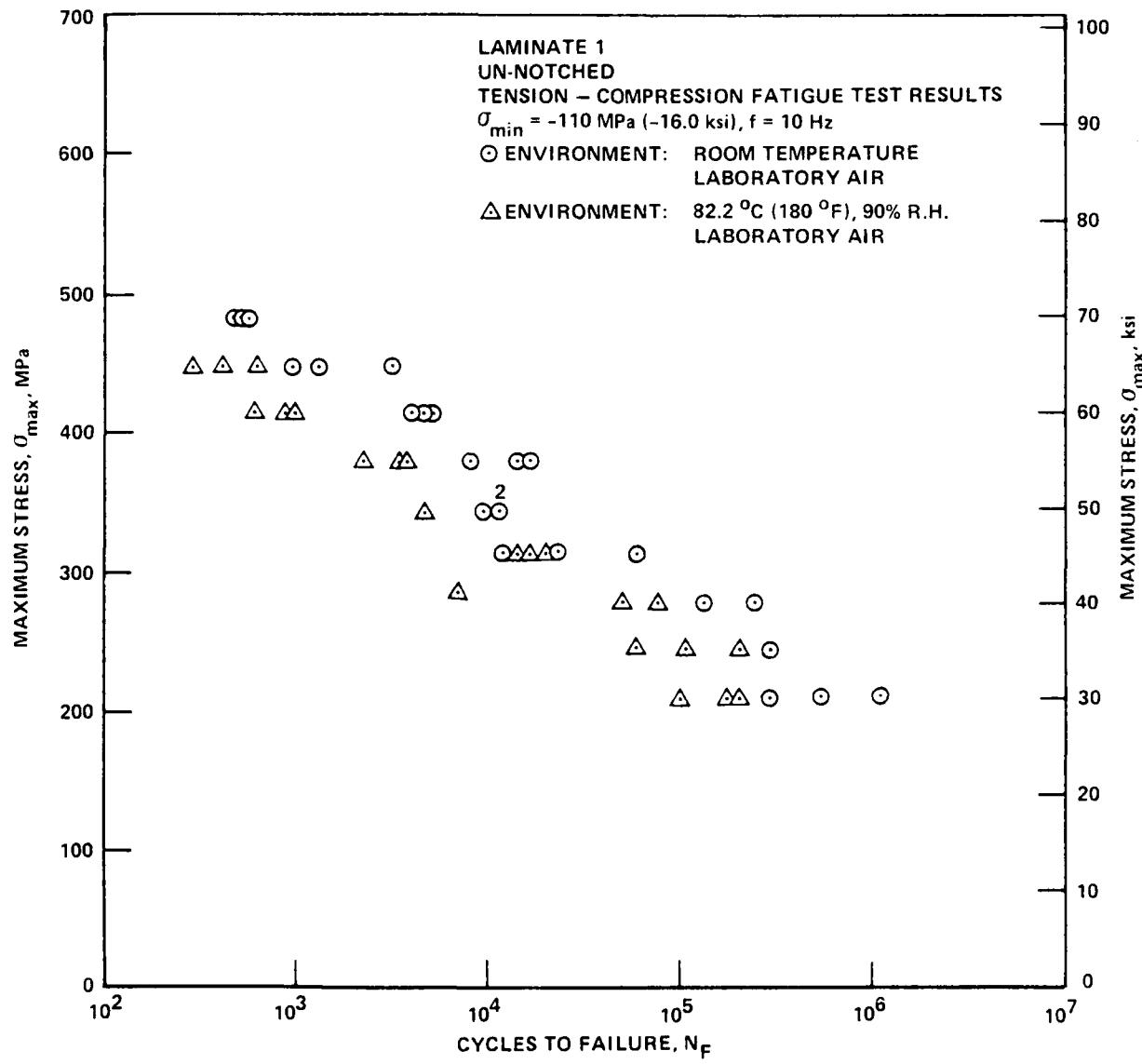
Figure 90. Comparison of Laminate 1 Un-notched Tension-Compression Fatigue
Stress-Life Results at Room Temperature and 82.2°C (180°F),
90% R.H.

176

Figure 91. Comparison of Laminate 1 Notched Tension-Tension Fatigue Stress-
Life Results at Room Temperature and 82.2°C (180°F), 90% R.H.

177
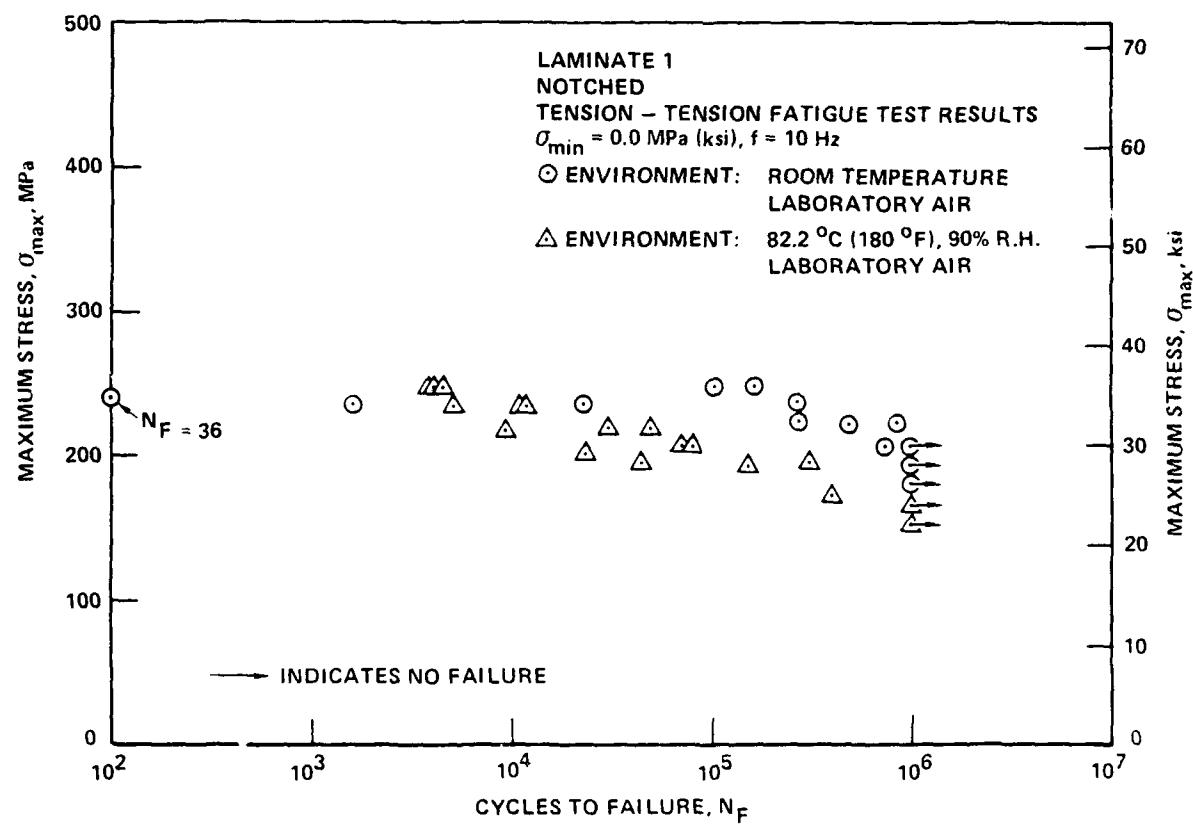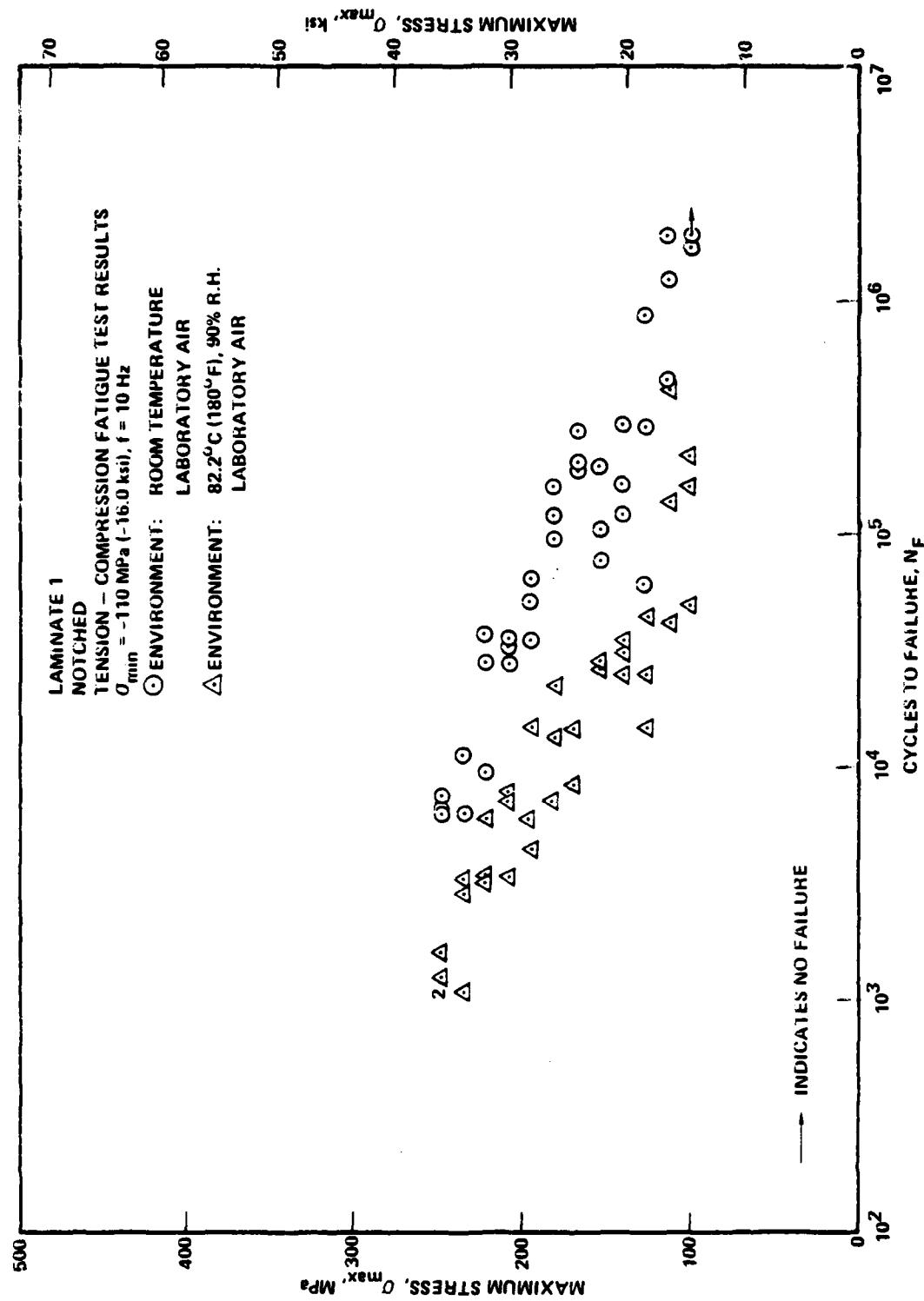
Figure 92. Comparison of Laminate 1 Notched Tension-Compression Fatigue Stress-Life Results at Room Temperature and 82.2°C (180°F), 90% R.H.

178
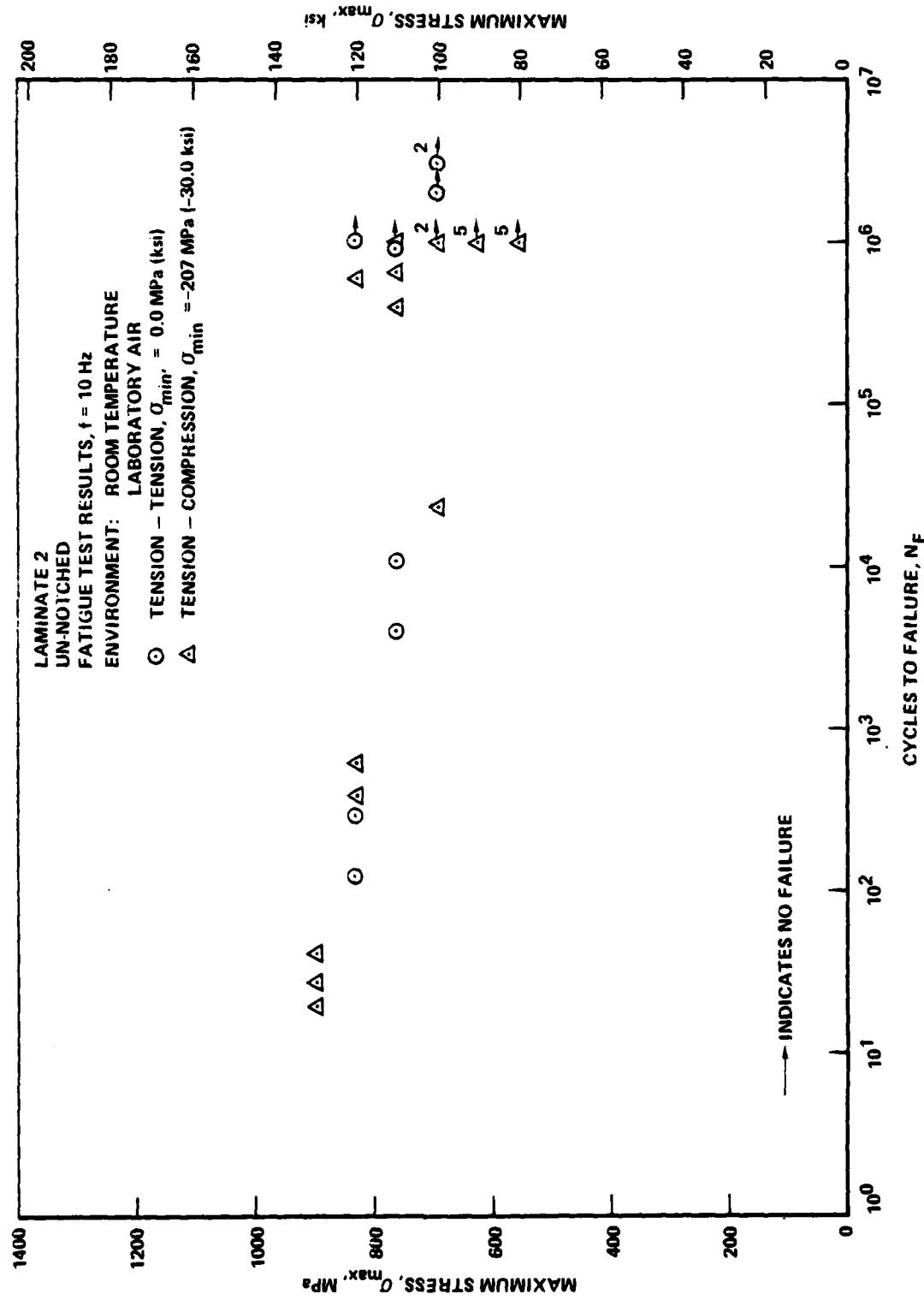
Figure 93. Comparison of Laminate 2 Un-notched Tension-Tension and Tension-Compression Fatigue Stress-Life Results at Room Temperature in Laboratory Air

179
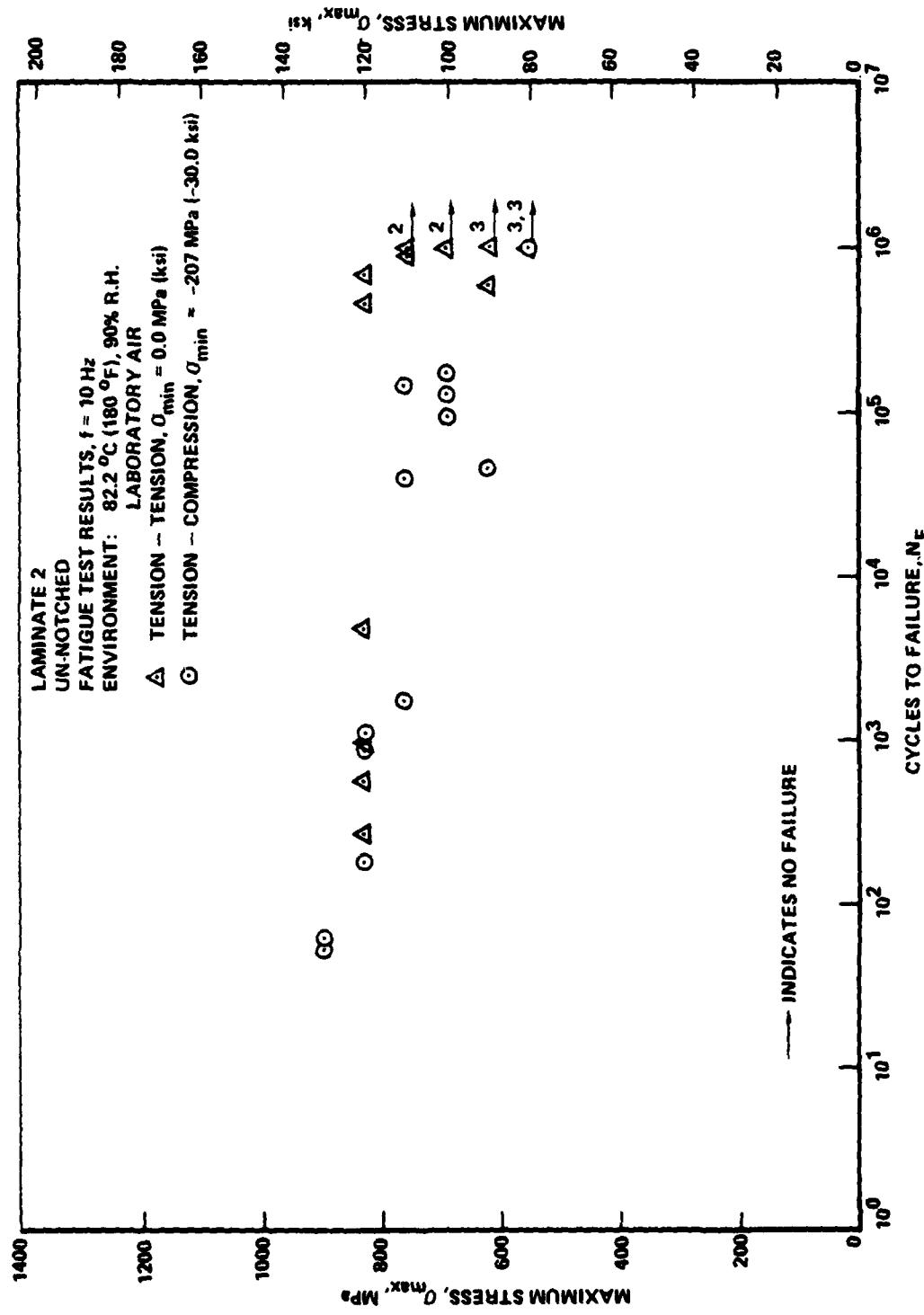
Figure 94. Comparison of Laminate 2 Un-notched Tension-Tension and Tension-Compression Fatigue Stress-Life Results at 82.2°C (180°F), 90% R.H., in Laboratory Air

180
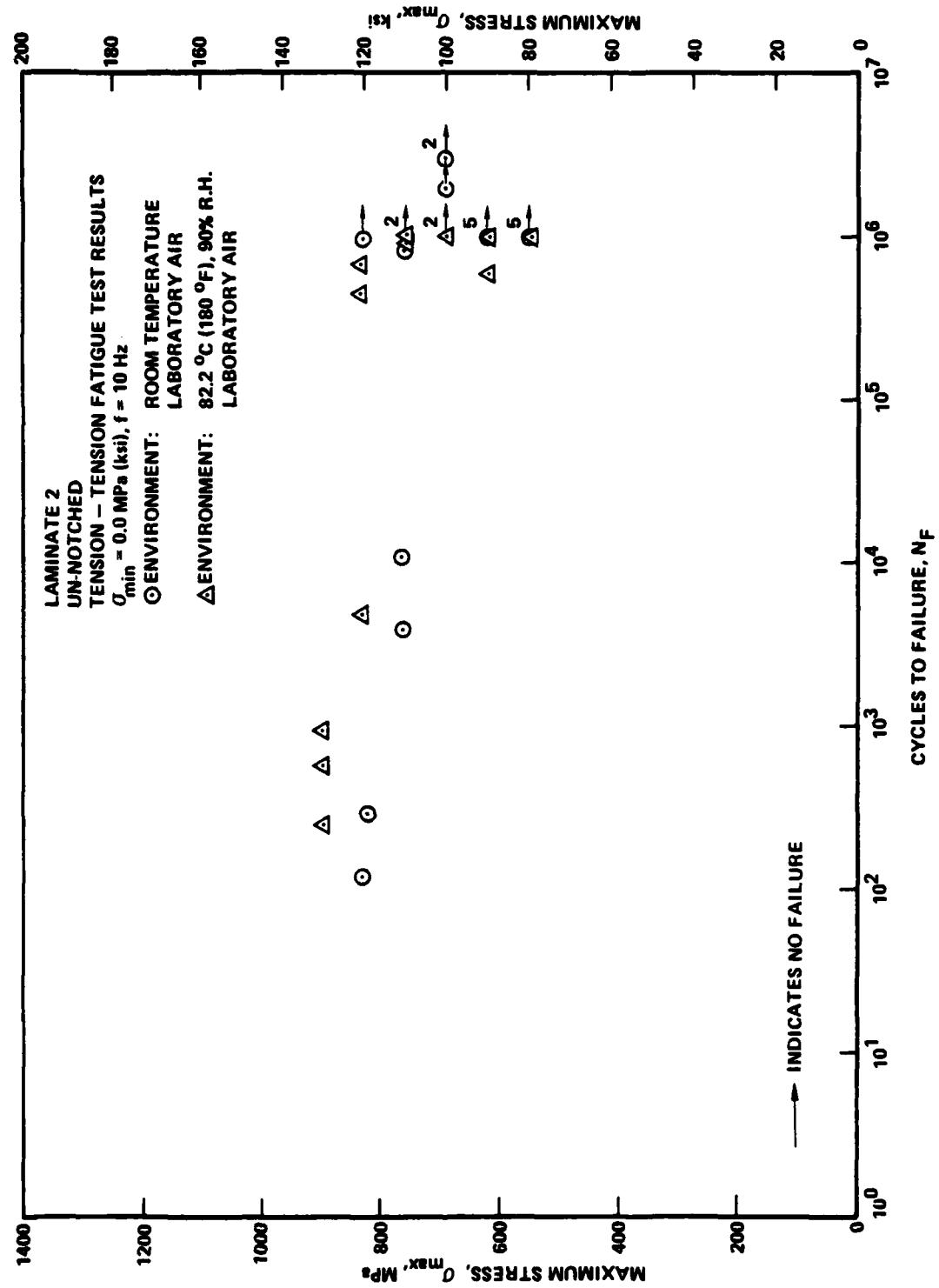
Figure 95. Comparison of Laminate 2 Un-notched Tension-Tension Fatigue Stress-Life Results at Room Temperature and 82.2°C (180°F), 90% R.H.
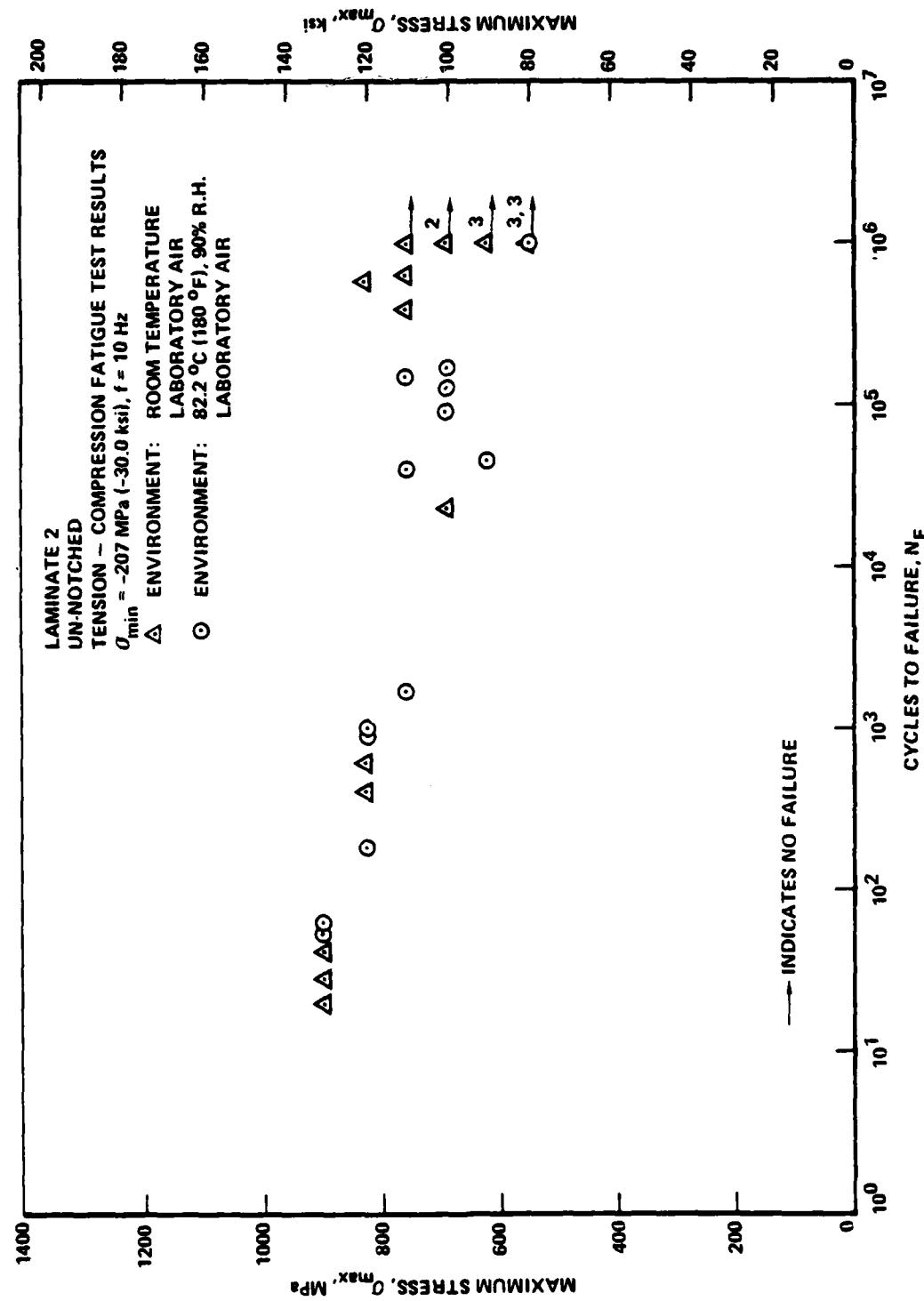
Figure 96. Comparison of Laminate 2 Un-notched Tension-Compression Fatigue Stress-Life Results at Room Temperature and 82.2°C (180°F), 80% R.H.

6.3   EXTENT OF FATIGUE SCATTER

Based on the stress-life results, specific σ_{max} stress levels were chosen to determine the extent of fatigue life scatter. For laminate 1, four σ_{max} levels were chosen for each S-N curve and fifteen coupons fatigue cycled to fatigue at each σ_{max} level. For laminate 2, only two stress levels were selected because of the large scatter, thus allowing for more accurate sampling. All of the data is tabulated in Appendix C. Since the fatigue scatter of un-notched coupons was previously determined [1] at room temperature, only the scatter at 82.2°C (180°F), 90% R.H. was obtained for the un-notched coupons.

6.3.1   Laminate 1

Un-Notched

For un-notched laminate 1 coupons at high temperature, stress levels at 207, 276, 345, and 414 MPa (30, 40, 50, and 60 ksi) were chosen to define the scatter of the tension-tension (T-T) fatigue curves and 137, 207, 276, and 345 MPa (20, 30, 40, and 50 ksi) for the tension-compression (T-C) fatigue curves. The highest stress level was chosen as representative of the life region where the maximum stress dominated the fatigue life while the lower two stress levels defined the life region where stress range was more predominant. A stress level of 345 MPa (50 ksi) appeared to be a region where the maximum stress and stress range were equally influencing the fatigue life. At each of these stress levels, fifteen coupons were fatigue cycled, including the original three, to failure under T-T or T-C loading.

Test results obtained to determine fatigue scatter for the un-notched laminate 1 coupons are shown in Figures 97 and 98. Each point on the plots represents a single data point. The data appears to be scattered over approximately 1 to 1-1/2 orders of magnitude. In both Figures 97 and 98, data are shown which were obtained from coupons tested at two different moisture levels, approximately 1.3% and 1.7% (see Section 4). For the T-T loading, the 1.3% moisture coupons had the highest fatigue lives at 345 and 414 MPa (50 and 60 ksi) while for the T-C loading this was true at every σ_{max} level. All of the
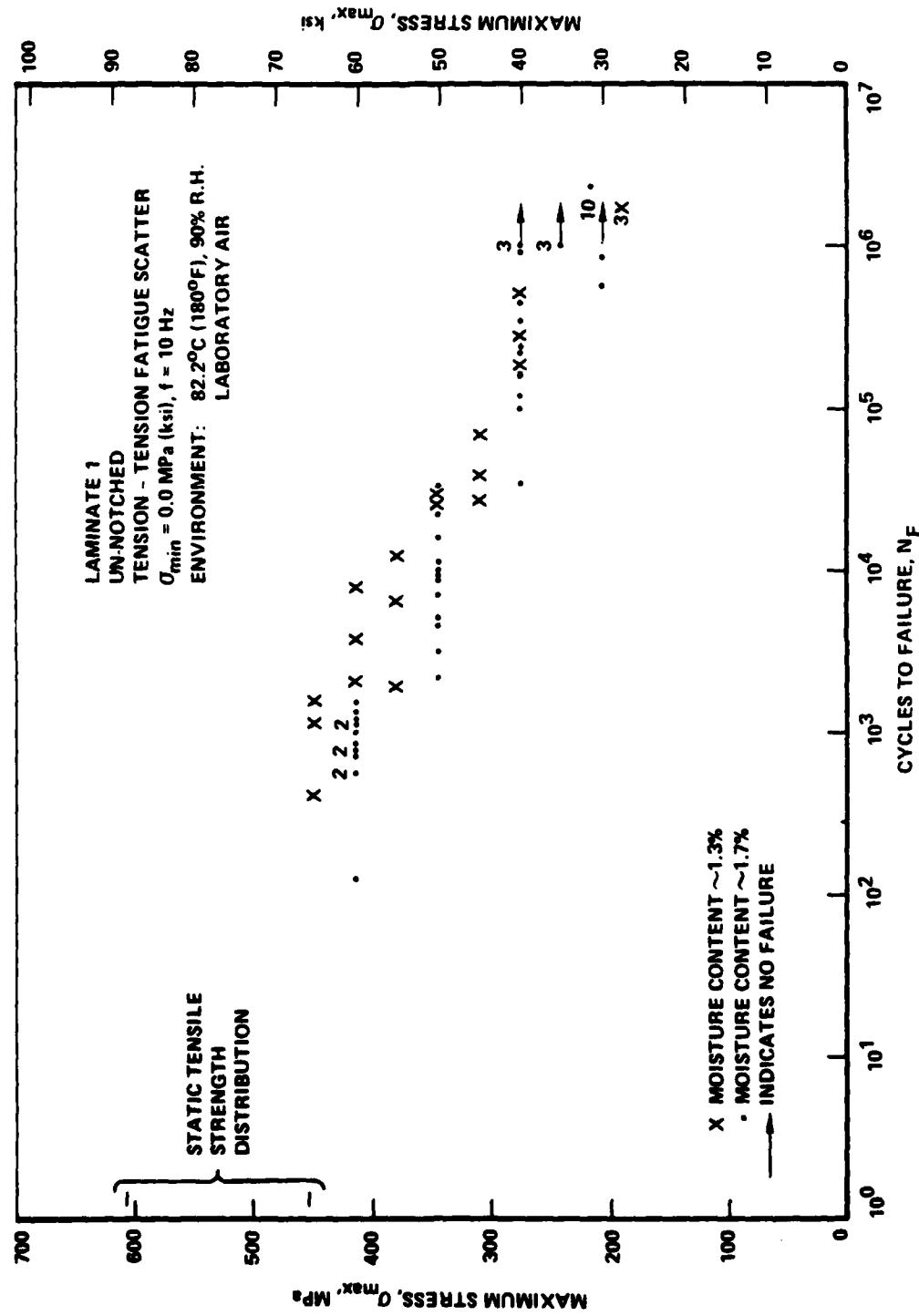
Figure 97. Laminate 1 Un-notched Tension-Tension Fatigue Scatter Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air

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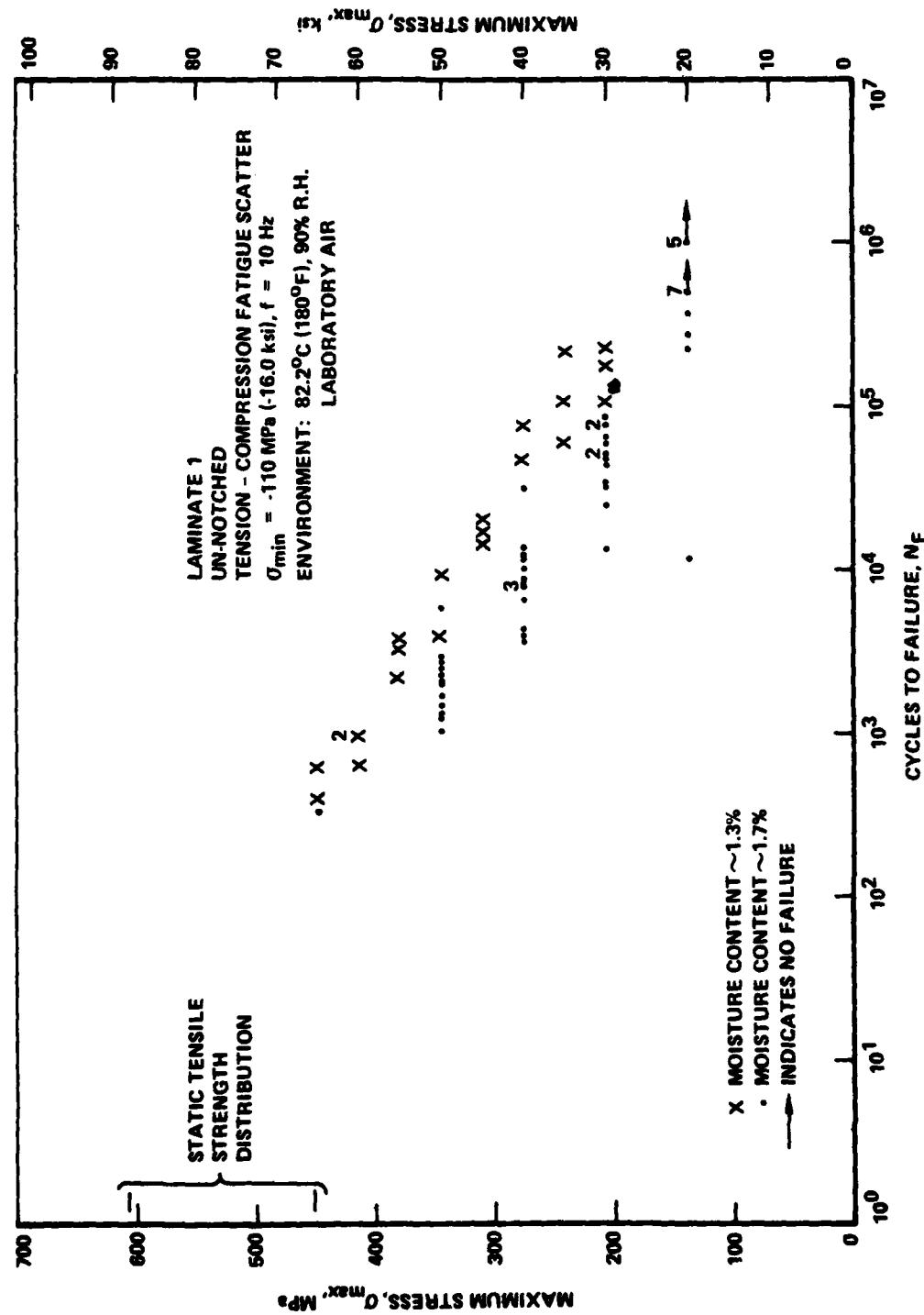
Figure 98. Laminate 1 Un-notched Tension-Tension Fatigue Scatter Results at 82.2°C (180°F), at 90% R.H. in Laboratory Air

three data points obtained at the other σ_{max} levels were from coupons with 1.3% moisture. If Figures 97 and 98 are closely inspected, one can see that the coupons with approximately 1.7% moisture content form a distinctly different and shorter life fatigue population than those with approximately 1.3% moisture content. The effect of moisture content on fatigue life is therefore, evident. If the data from the two moisture levels is separated, the fatigue scatter is significantly reduced. This is apparent in Figures 97 and 98 and in Table 37 which shows the Weibull coefficients for this data.

Notched

The laminate 1 fatigue scatter results of notched coupons are shown in Figures 99-102. At room temperature, the T-T data confirmed the expected rather flat curve with large scatter at the higher σ_{max} levels near or at the static strength lower limit. The T-C data at room temperature, Figure 100, scattered over approximately one order of magnitude at each σ_{max} level similar to the un-notched data. At 82.2°C (180°F), 90% R.H., the scatter of these notched coupons was also approximately one order of magnitude at each stress level. The presence of the notch reduced fatigue life, but did not significantly affect the apparent, intrinsic material scatter. The three data points generated at each of several stress levels to determine the S-N curve at high temperature were obtained using coupons which had a moisture content of approximately 1.5%. The coupons used to determine the extent of scatter had an average moisture content of approximately 1.7%. The data in Figures 99 to 102 was fitted with a three parameter Weibull fit using the procedures of Section 2.6. Results for the group are tabulated in Tables 38 and 29 since no effect of the notched fatigue data could be discerned.

6.3.2 Laminate 2

Because of the large apparent scatter of the laminate 2 fatigue data, the same procedure for choosing σ_{max} levels to define the fatigue life scatter could not be used as was used for laminate 1. Therefore, for T-T loading, twenty (20) coupons were cycled to failure or to 10^6 cycles at 827 MPa (120 ksi) while at 689 MPa (100 ksi) thirty-seven (37) coupons were fatigue

TABLE 37

WEIBULL PARAMETERS AND ESTIMATES FOR UN-NOTCHED
LAMINATE 1 FATIGUE SCATTER DATA TESTED AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

Stress (ksi)		Weibull Coefficients			Average Cycles to Failure	Correlation Coefficient, R
max	min	k	e	v		
207 (30)	0	_a	--	-	$>10^6$	-
276 (40)	0	_b	-	-	$>5 \times 10^5$	-
345 (50)	0	1.063[c] / 1.060	580.6 / 1287	12,981 / 9,678	13,154 / 10,759	0.9903 / 0.9912
414 (60)	0	2.210[c] / 3.502	-107.0 / -224.6	1,146 / 989	1,431 / 899	0.9841 / 0.9850
138 (20)	-110 (-16)	_d	-	-	$>5 \times 10^5$	-
207 (30)	-110 (-16)	1.474[e] / 1.956	0 / 0	81,746 / 59,024	72,510 / 50,728	0.9734 / 0.9857
276 (40)	-110 (-16)	1.080[e] / 1.703	0 / 0	18,081 / 11,642	17,354 / 10,193	0.8962 / 0.9369
345 (50)	-110 (-16)	0.755[c] / 2.932	970.3 / -44.5	2,363 / 2,234	2,937 / 2,145	0.9891 / 0.9947

a - No values calculated. all but 2 coupons remained unfailed at 10^6 cycles.

b - No values calculated. three coupons remained unfailed at 10^6 cycles.

c - First value is 3-parameter fit for all data, second value is that for 1.7% average moisture content only.

d - No values calculated. all but three coupons remained unfailed.

e - First value is 2-parameter fit for all data, second value is that for 1.7% average moisture content only.
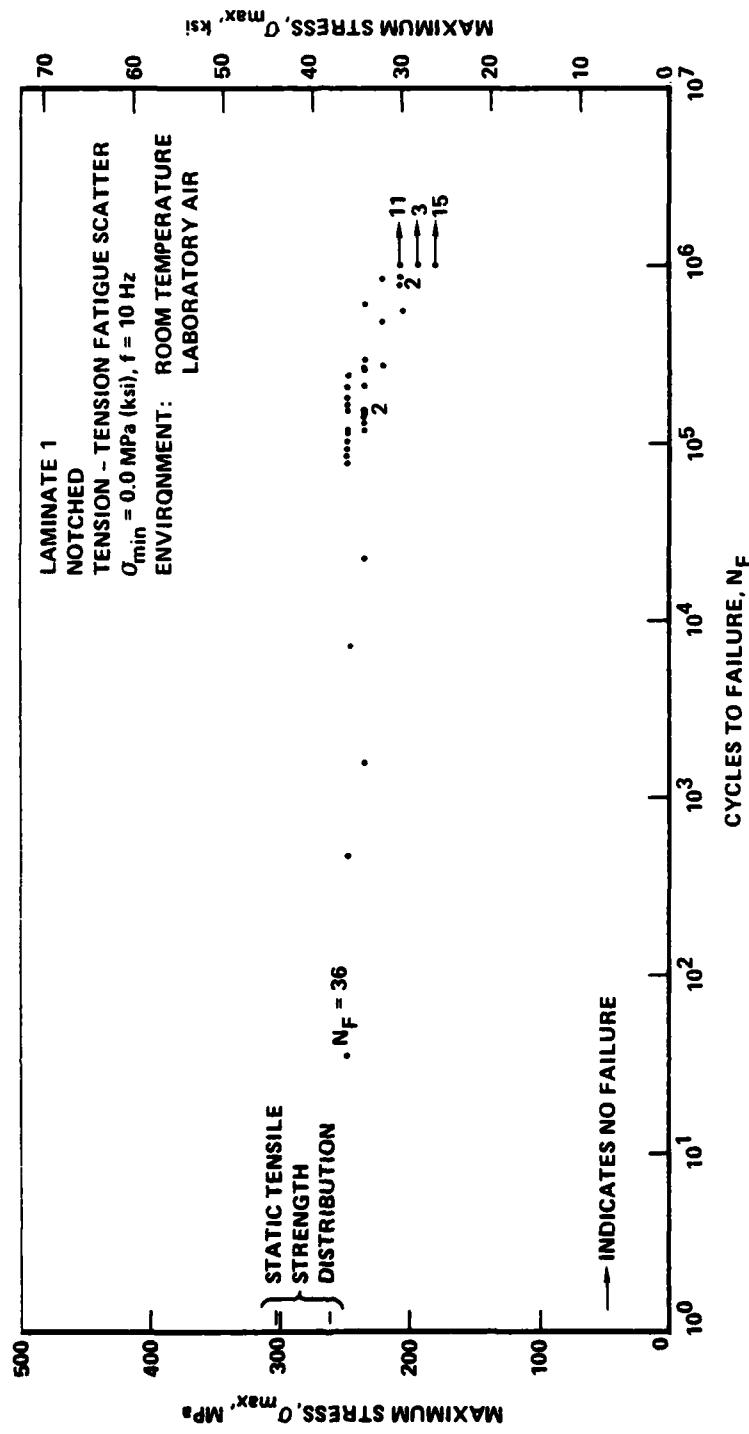
Figure 99. Laminate 1 Notched Tension-Tension Fatigue Test Results at σ_{min} = 0 MPa

188
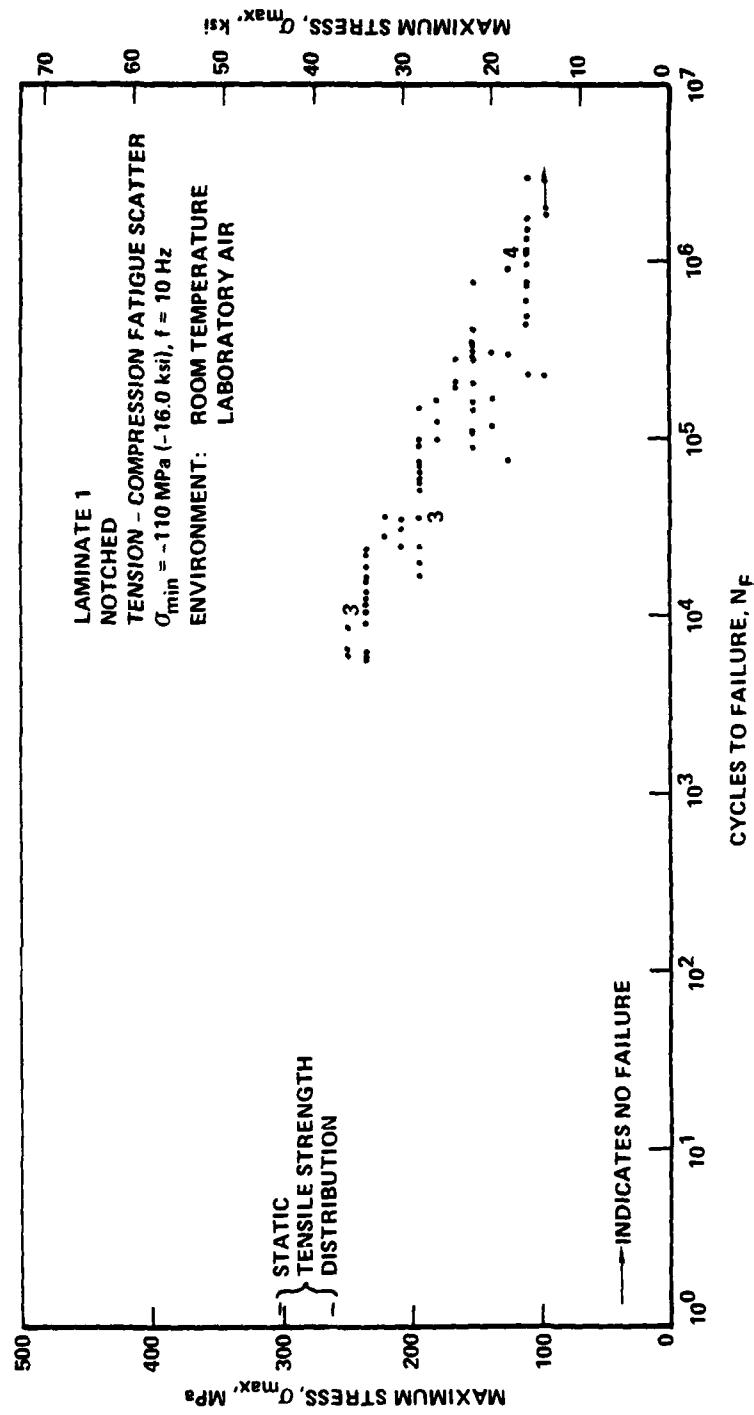
Figure 100. Laminate 1 Notched Tension-Compression Fatigue Test Results at σ_{min} = -110 MPa (-16 ksi)

189
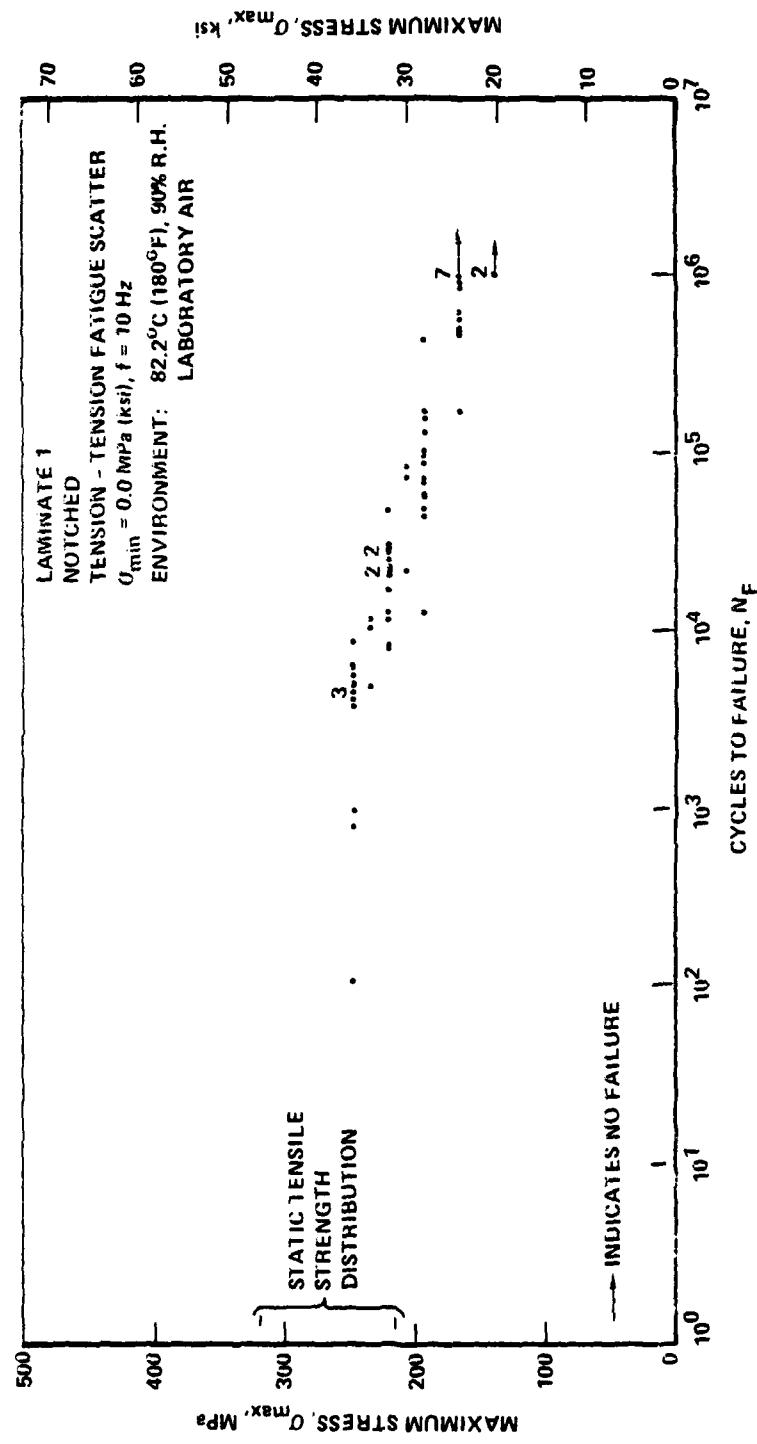
Figure 101. Laminate 1 Notched Tension-Tension Fatigue Scatter Results at 82.2°C (180°F) at 90% R.H. in Laboratory Air
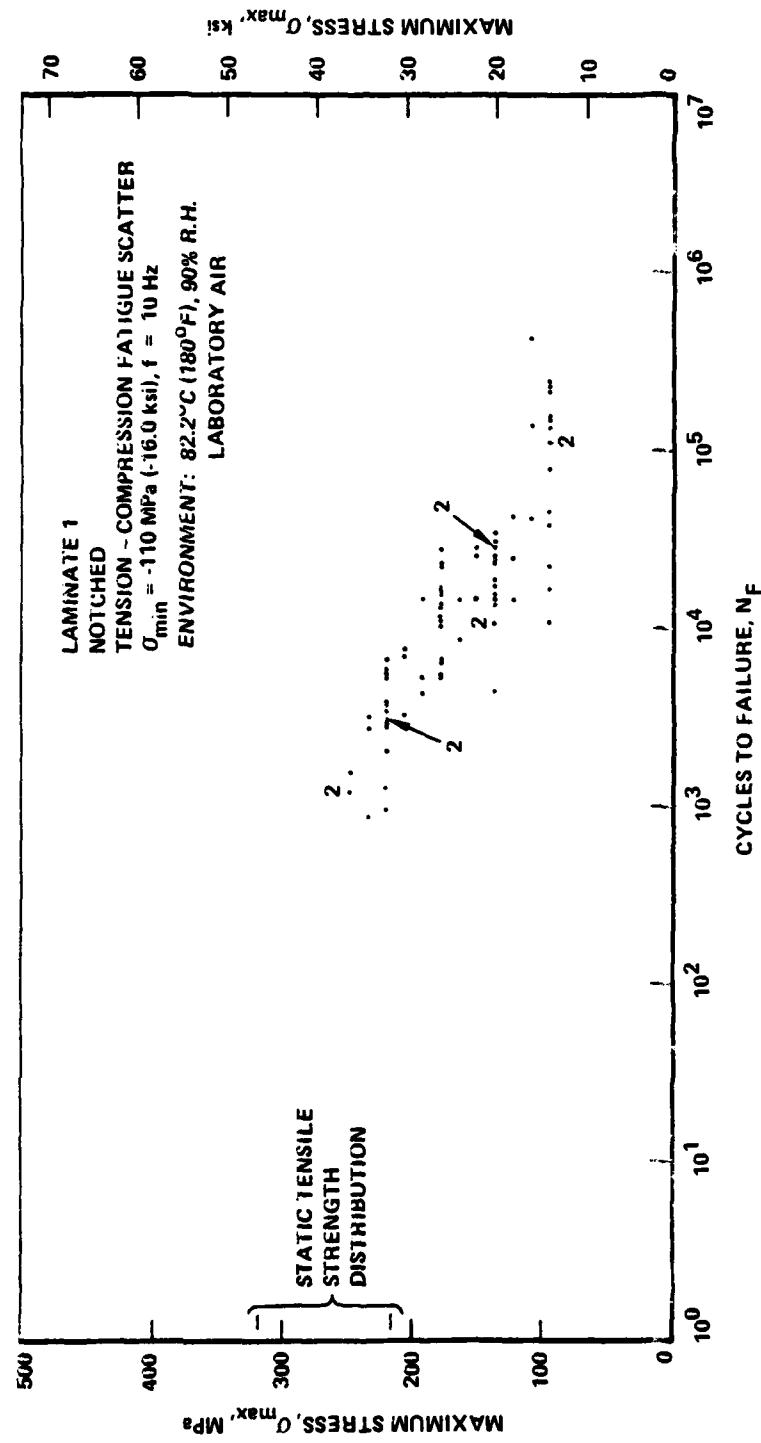
Figure 102. Laminate 1 Notched Tension-Compression Fatigue Scatter Results at 82.2°C (180°F) at 90% R.H. in Laboratory Air

TABLE 38

WEIBULL PARAMETERS AND ESTIMATES FOR
NOTCHED LAMINATE 1 FATIGUE DATA
ROOM TEMPERATURE, LABORATORY AIR

(15 Coupons/Stress Level)

Stress MPa (ksi)		Weibull Coefficients			Average Cycles to Failure	Correlation Coefficient, R
max	min	k	e	v		
179 (26)	0	a	-	-	$> 10^6$	-
207 (30)	0	a	-	-	$> 10^6$	-
234 (34)	0	1.317 b 0.652	-4,288 0	211,856 290,019	213,219	0.9642 0.8851
248 (36)	0	3.178 0.362	-90,345 0	139,721 184,454	117,667	0.9842 0.8719
110 (16)c	-110 (-16)	2.686 1.669	-159,004 0	1,068,617 1,198,875	1,043,689	0.9953 0.9836
152 (22)	-110 (-16)	3.153 1.707	-77,917 0	296,435 326,890	284,610	0.9845 0.9712
193 (28)	-110 (-16)	2.365 1.706	-7,484 0	60,750 66,718	58,231	0.9915 0.9832
234 (34)	-110 (-16)	1.647 2.370	2,389 0	13,147 14,366	12,613	0.9906 0.9745

a - No values calculated because there were no failures at 179 MPa (26 ksi) and only 4 at 207 MPa (30 ksi)

b - First value is 3-parameter fit, second is a classic 2-parameter.

c - 16 data points analyzed

TABLE 39

WEIBULL PARAMETERS AND ESTIMATES FOR NOTCHED LAMINATE 1 FATIGUE SCATTER DATA TESTED AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

Stress MPa (ksi) max	min	Weibull Coefficients k	e	v	Average Cycle to Failure	Correlation Coefficient, R
(24)	0	-a	-	-	> 10^6	-
(28)	0	1.918[b] / 1.286	-4,239.9 / 0	99,880 / 122,851	108,663	0.9910 / 0.9500
(32)	0	3.782 / 2.090	-4,755.8 / 0	22,977 / 25,127	21,852	0.9862 / 0.9746
(36)	0	4.899 / 0.794	-3,585.7 / 0	4,952 / 5,811	4,324	0.9649 / 0.8034
(14)	-110(-16)	1.799 / 1.009	-34,948 / 0	125,465 / 127,439	111,499	0.9899 / 0.9842
(20)	-110(-16)	3.164 / 1.923	-4,412 / 0	22,253 / 23,466	20,123	0.9906 / 0.9778
(26)	-110(-16)	2.333 / 2.100	-453.9 / 0	14,388 / 15,428	13,466	0.9880 / 0.9783
(32)	-110(-16)	3.055 / 1.897	-837.2 / 0	3,899 / 4,078	3,498	0.9837 / 0.9764

a - No value calculated. 7 of 15 coupons remained unfailed at 10^6 cycles.

b - First value is 3-parameter fit, second is a classic 2-parameter

cycled until failure or to 10^6 load cycles. Similar procedures were used for T-C testing at σ_{max} levels of 689 and 551 MPa (100 and 80 ksi). Results are shown in Figures 103 and 104. As previously found at room temperature, Reference 1, the scatter in fatigue life was large. At a fatigue load of 0 to 689 MPa (0 to 100 ksi), the majority of coupons survived 10^6 cycles while at 0 to 827 MPa (0 to 120 ksi) scatter was greater than three orders of magnitude. The unfailed coupons under T-T and T-C loading at 689 and 551 MPa (100 and 80 ksi), respectively, were tested statically for residual strength, half in tension and half in compression. Many of these coupons did not fail in the sense of no longer holding load, however, they were severely damaged as evidenced by extreme shredding of the outer plies. This was quite different than at room temperature [1] where the unfailed coupons suffered little or no visible damage. This was supported by the fact that room temperature coupons suffered no loss in tensile sttength. Thus, a significant effect of the high temperature environment on the fatigue properties of un-notched laminate 2 coupons was observed.

6.4   LONG LIFE FATIGUE TESTING OF LAMINATE 1 COUPONS

Using coupons fabricated under a previous Air Force contract (F33615-75-C-5118, Ref. 1), the possibility of a fatigue threshold for laminate 1 was investigated by increasing the number of cycles of previously tested coupons. Results of the tests conducted are tabulated in Appendix C. Of the 20 tests conducted, 3 coupons failed before reaching the 10^7 cycle "run-out". Figure 105 shows the original T-T fatigue data plotted as σ_{max} versus cycles to failure, N_F, while Figure 106 shows the addition of the new data at σ_{max} = 231 MPa (33.5 ksi) (equivalent to a strain range of ~ 0.0044 mm/mm). Figure 106 shows that no fatigue threshold was apparent down to this maximum stress level.

Because a previous report [1] indicated that at these lower σ_{max} levels fatigue life is related to stress or strain range, the expected T-C fatigue life distribution at R = -1 and ϵ = .0021 mm/mm or $\Delta\epsilon$ = .0042 mm/mm could possibly be ascertained. Figure 107 shows the previous T-C data for laminate 1, and the
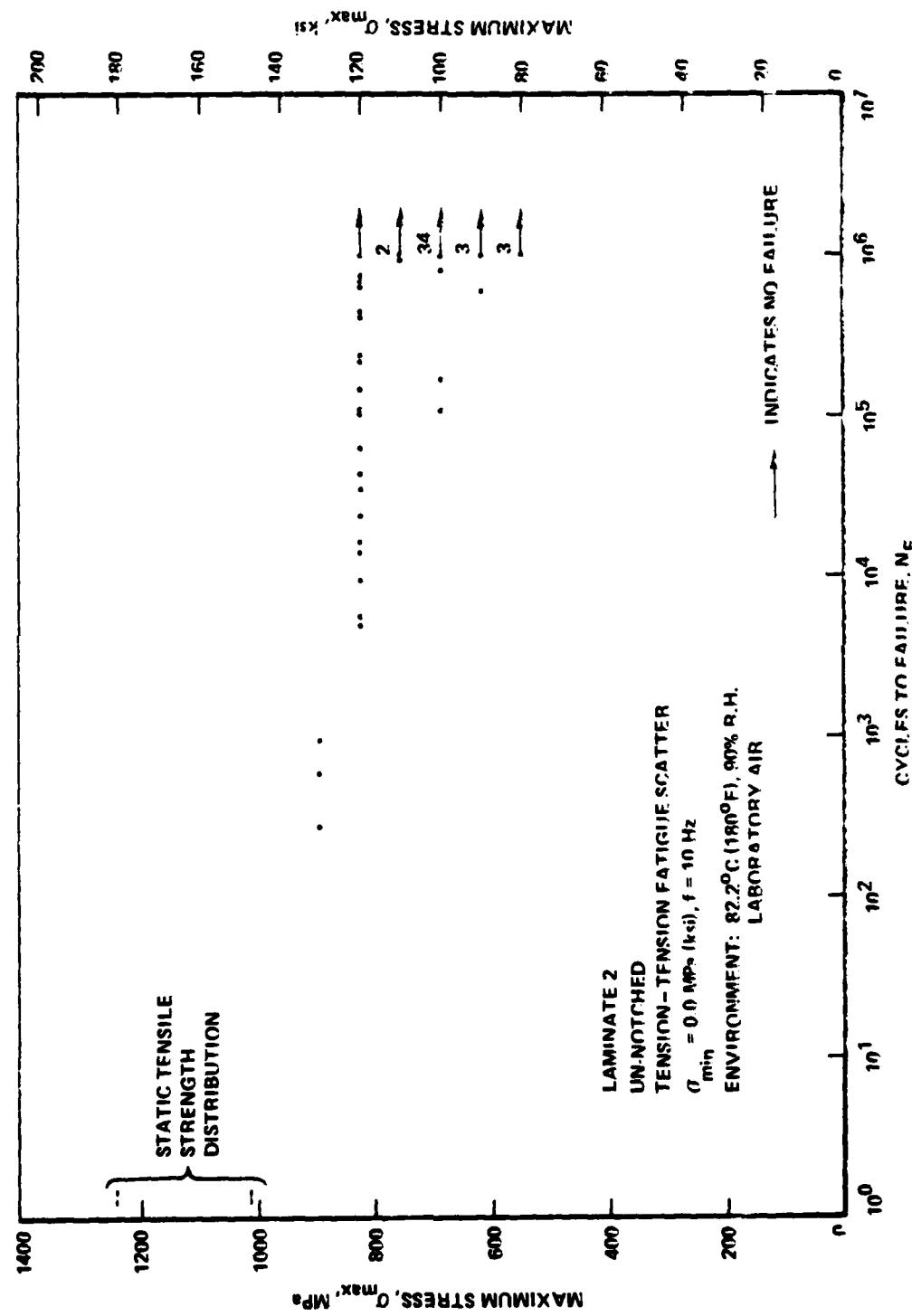
Figure 1.03. Laminate 2 Un-notched Tension-Tension Fatigue Scatter Results at 82.2°C (180°F) at 90% R.H. in Laboratory Air

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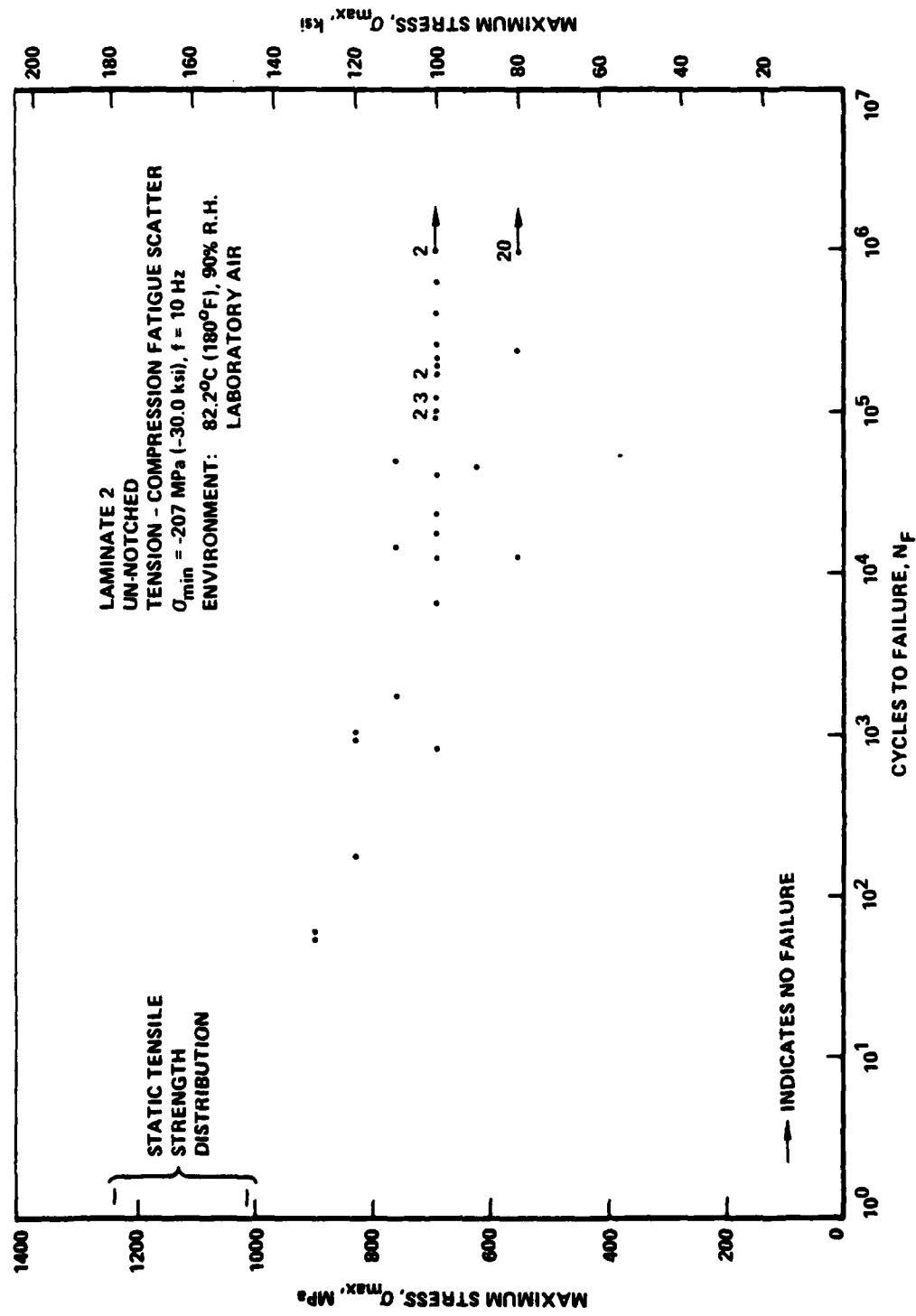
Figure 104. Laminate 2 Un-notched Tension-Compression Fatigue Scatter Results at 82.2°C (180°F) at 90% R.H. in Laboratory Air
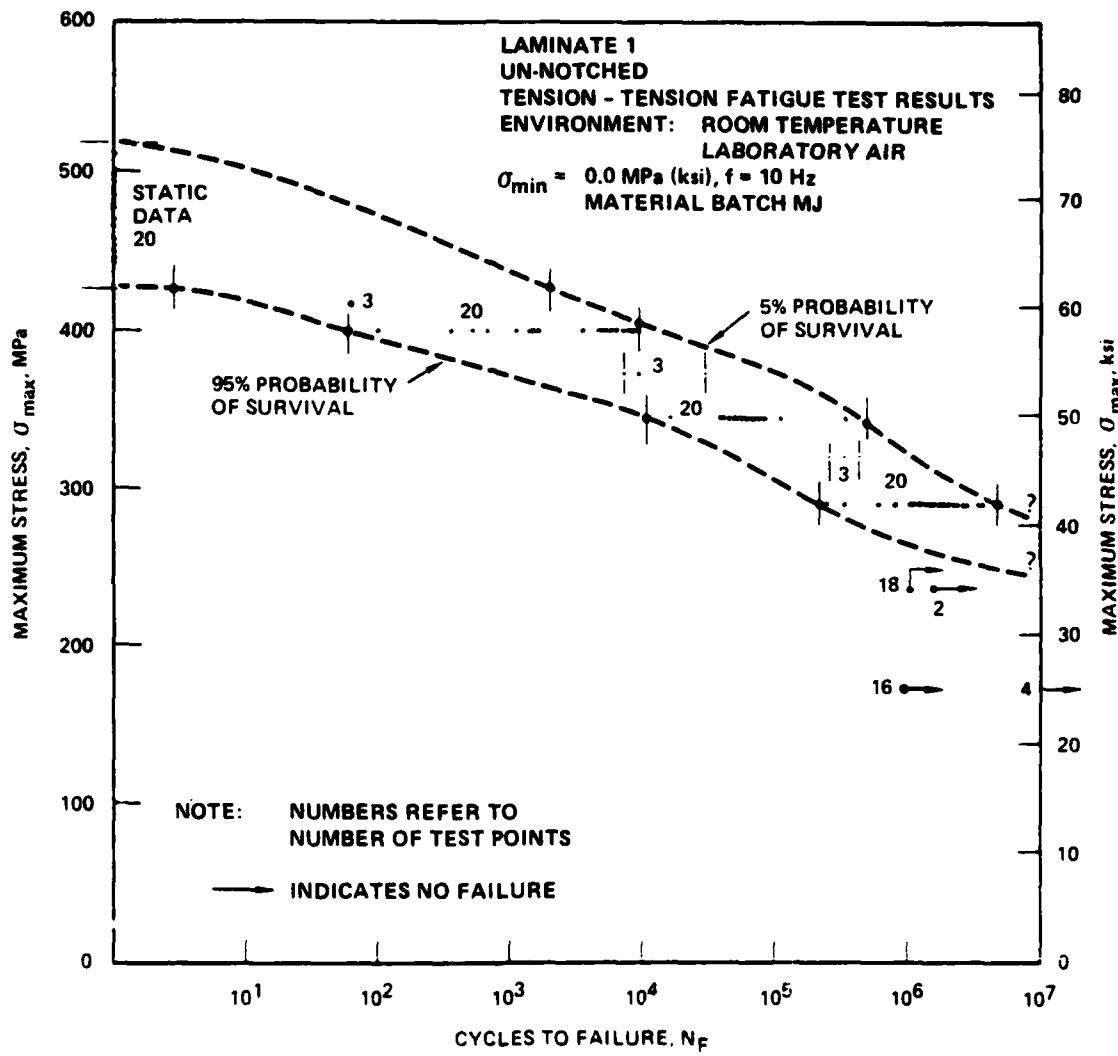
Figure 105. Laminate 1 Tension-Tension Fatigue Results at σ_{min} = 0.0 MPa (ksi)

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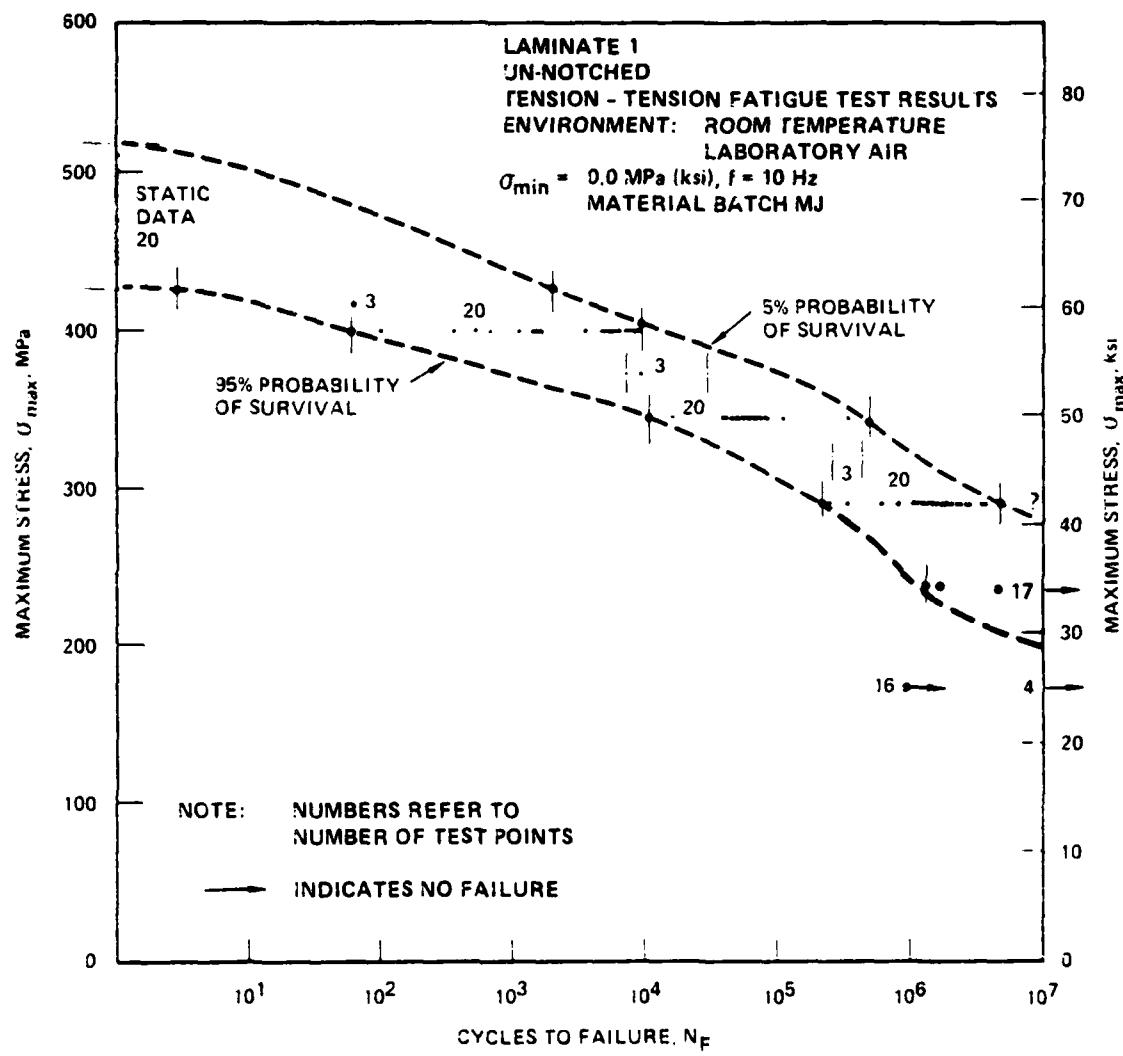
Figure 106. Laminate 1 Tension-Tension Fatigue Results at σ_{min} = 0.0 MPa (ksi) with addition of Data at σ_{min} = 33.5 ksi

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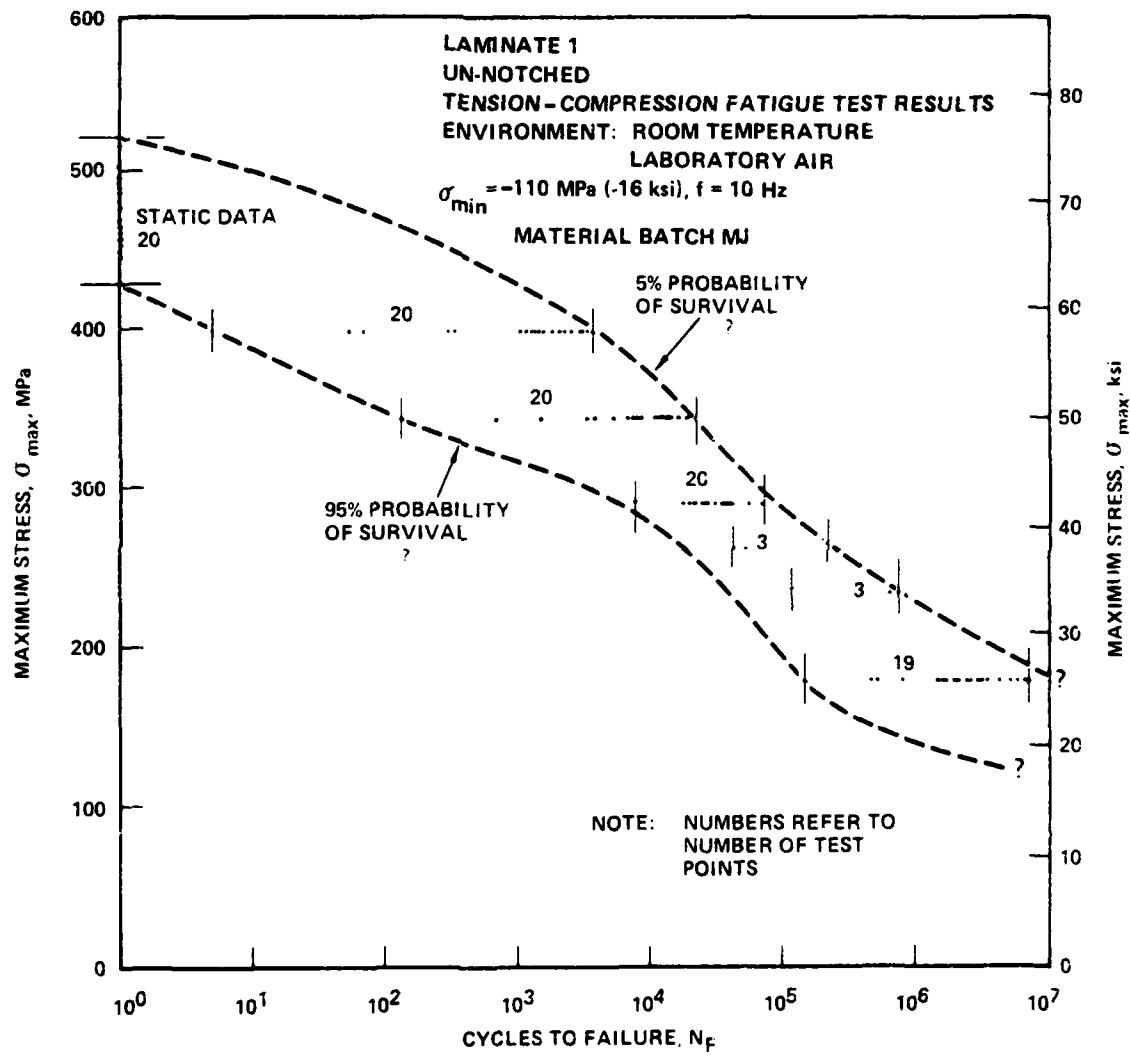
Figure 107. Laminate 1 Tension-Compression Fatigue Test Results at σ_{min} = -110 MPa (16.0 ksi)

expected curve shape at σ_{max} = 110 MPa (16 ksi). The validity of this projection was evaluated. Twenty coupons were tested under T-C fatigue loading at -110 to 110 MPa (-16 to 16 ksi). Results are tabulated in Appendix C, only one coupon failed to reach 10^7 cycles. Figures 108 shows that the minimum life in the fatigue scatter under T-C loading is similar to that under T-T loading, Figure 106, for the same strain range.
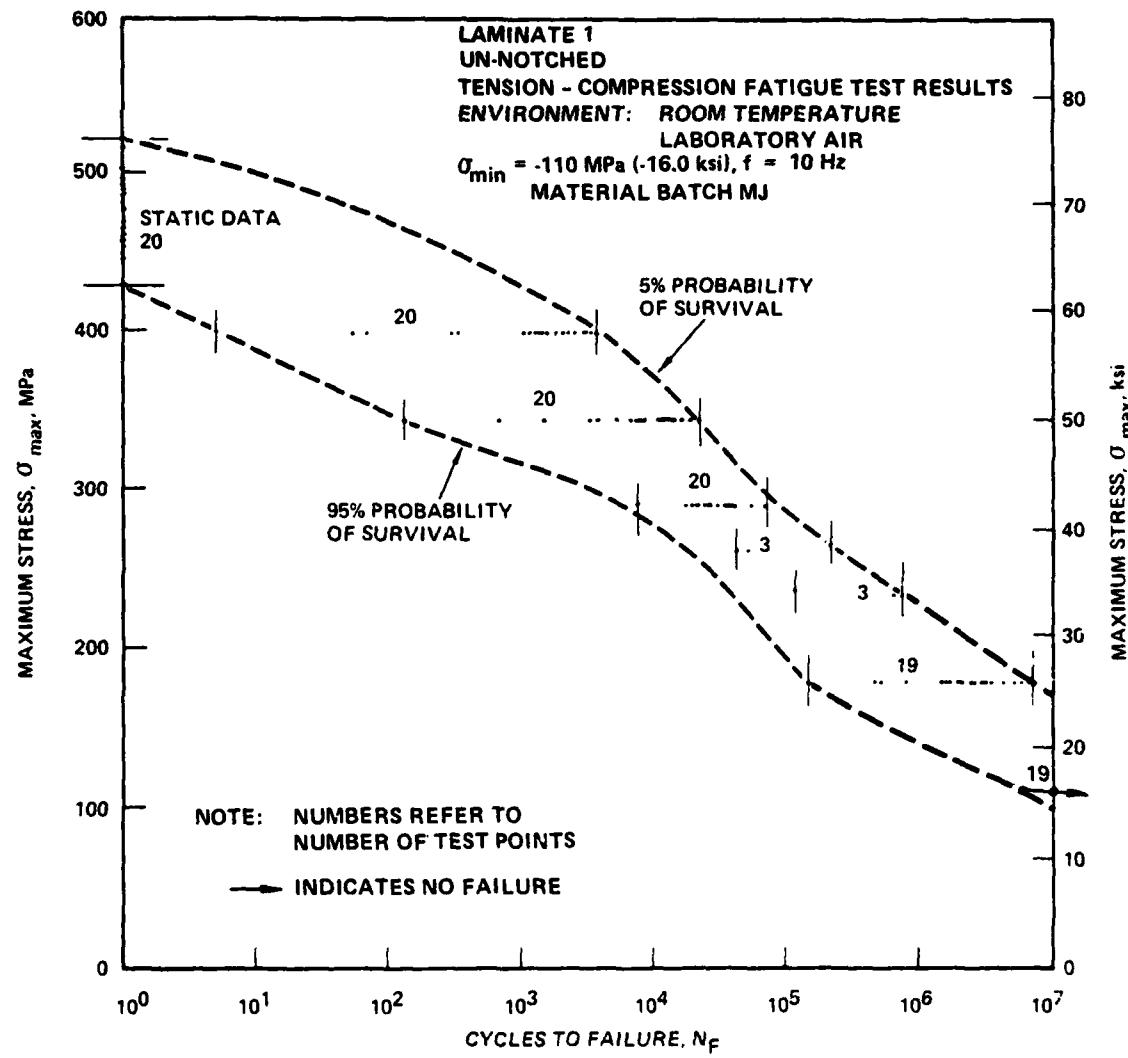
Figure 108. Laminate 1 Tension-Compression Fatigue Test Results
at σ_{min} = -110 MPa (16.0 ksi)

SECTION VII

RESIDUAL STRENGTH TESTING RESULTS

For both laminates, whether un-notched or notched, residual strength was
determined at one maximum stress level selected from each fatigue test
condition. At each selected stress level, coupons from the appropriate
laminate were fatigue cycled to one of two different cyclic lives after
which half were failed in static tension and half in compression. Where
possible, the two different cyclic lives were chosen as those equivalent to
a probability of survival of $P_{0.90}$ and $P_{0.50}$ based upon the previously deter-
mined fatigue scatter (see Section 6.3). Coupons which failed in fatigue
were replaced by additional coupons until at least twenty static residual
strength test results were obtained for each fatigue/static test condition
or until all available coupons were tested.

Un-notched laminate 1 and laminate 2 residual strength coupons were fatigue
cycled at 82.2°C (180°F), 90% R.H. in laboratory air while notched laminate
1 coupons were fatigue tested in this environment as well as at room temper-
ature in laboratory air. Static tests of coupons prior fatigue tested at
82.2°C (180°F) were conducted at this same temperature using the static
test procedures previously described (see Section 2). The data for all of
the residual strength tests are tabulated in Appendix D.

The residual strength testing procedure encountered three complications.
First, the average moisture content of most of the un-notched fatigue scatter
coupons was higher than that of the residual strength coupons (1.7% versus
1.3%). Since the estimated cycle lives corresponding to $P_{0.90}$ or $P_{0.50}$
were based upon the fatigue scatter data and since their correspondingly
higher moisture content reduces the fatigue life, the actual probability
of survival values for un-notched coupons were often closer to $P_{0.95}$ and
$P_{0.60}$. Second, for un-notched laminate 1 coupons tested under tension-

tension loading, only the 276 MPa (40 ksi) stress level, of the four stress
levels selected for the fatigue scatter study, seemed appropriate for resi-
dual strength testing. The other stress levels resulted in unfailed coupons
or in such short lives that they seemed unreasonable for further study.
However, at 276 MPa (40 psi) some coupons did not fail before the previously
selected runout life of 1×10^6 cycles and therefore the cyclic lives for
residual strength testing were arbitraily selected at 100,000 and 300,000
cycles as estimates of $P_{0.90}$ and $P_{0.50}$. Third, laminate 2 coupons tested
in fatigue largely remained unfailed at 10^6 cycles, though often heavily
delaminated in the outer two surface plies. Therefore, cycle lives for
residual strength testing were arbitraily selected as 2.5×10^5 and 1×10^6
cycles.

7.1 Laminate 1 Residual Strength Results

Un-notched

Table 40 is a summary of the residual strength data for un-notched laminate
1 coupons fatigue tested at 82.2°C (180°F), 90% R.H. in laboratory air. The
high temperature environment residual strength results were similar to those
previously obtained in a room temperature environment (1). This is apparent
in the histogram of Figure 109 and in Table 40. The overall effect of the
higher temperature environment was to greatly increase the effect of fatigue
on the residual static strength compared to room temperature results. At
room temperature, fatigue cycling at more severe stress ranges screened more
coupons by early failure resulting in increased residual strength of the
remaining coupons. This also occurred at high temperatures where the strength
of coupons tested at 0 to 276 MPa (0 to 40 ksi) were lower than those tested
at -110 to 207 MPa (-16 to 30 ksi). The residual strength of coupons tested
after being subjected to fatigue cycles equivalent to $P_{0.50}$ were lower than
those obtained after fatigue cycles equivalent to $P_{0.90}$. These results are
consistent with those observed for other materials.

These two seemingly contradictory results appear to have a simple explanation.
An idealized graph of the materials strength degradation is shown in Figure
110. From this figure, the average residual strength at $P_{0.90}$ for those

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TABLE 40

SUMMARY OF RESIDUAL STRENGTH TEST RESULTS FOR UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED

AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

Fatigue Stress Levels MPa / ksi	Probability of Survival P_s	Equivalent Cyclic Life Cycles[b]	Weibull Parameters[a] k	e	v	Correlation Coefficient, R	Average Ult. Stress σ avg. MPa / ksi	Average Ult. Strain, ε avg mm/mm in 50.8 mm	Average Secant Modulus to Failure, E_{SF} GPa / psi × 10⁶
Tension Test Results									
Before Fatigue	-	-	18.995[c] / 15.978	-0.5630 / 0	82.362 / 83.083	0.99687 / 0.9481	55 / 80.6	0.0109	51.0 / 7.39
0 to 276 0 to 40	0.90[a]	100,000	11.272 / 10.237	-0.7367 / 0	67.911 / 68.579	0.9961 / 0.9778	452 / 65.5	0.0092	48.7 / 7.07
0 to 276 0 to 40	0.70[a]	300,000	9.865 / 7.960	-1.5108 / 0	61.197 / 62.365	0.9893 / 0.9380	401 / 58.1	0.0091	44.5 / 6.46
-110 to 207 -16 to 30	0.90	17,750	15.078 / 14.315	-0.1307 / 0	76.393 / 76.965	0.9993 / 0.9929	513 / 74.4	0.0096	53.8 / 7.80
-110 to 207 -16 to 30	0.50	63,750	9.303 / 7.520	-2.3496 / 0	75.131 / 75.998	0.99114 / 0.95625	493 / 71.5	0.0095	52.0 / 7.54
Compression Test Results									
Before Fatigue	-	-	13.151 / 11.439	-0.5572 / 0	72.195 / 73.088	0.99704 / 0.97359	483 / 70.1	0.0114	43.0 / 6.23
0 to 276 0 to 40	0.90[a]	100,000	6.592 / 4.451	-2.6670 / 0	42.264 / 44.511	0.98690 / 0.94500	280 / 40.6	0.0064	43.4 / 6.30
0 to 276 0 to 40	0.70[a]	300,000	4.548 / 3.707	-3.5464 / 0	28.542 / 29.060	0.96997 / 0.93416	183 / 26.5	0.0045	39.2 / 5.68
-110 to 207 -16 to 30	0.90	17,750	8.488 / 7.970	-0.9367 / 0	58.961 / 59.476	0.99387 / 0.96711	388 / 56.2	0.0086	45.6 / 6.61
-110 to 207 -16 to 30	0.50	63,750	14.403 / 10.476	-0.9815 / 0	54.575 / 55.801	0.99145 / 0.9003	367 / 53.3	0.0087	42.6 / 6.18

a - Estimated value, fatigue run-outs occurred at this stress level

b - Calculated from a least square, 3-parameter Weibull analysis

c - First entry is 3-parameter, double logarithmic Weibull fit; second entry is classical 2-parameter Weibull fit
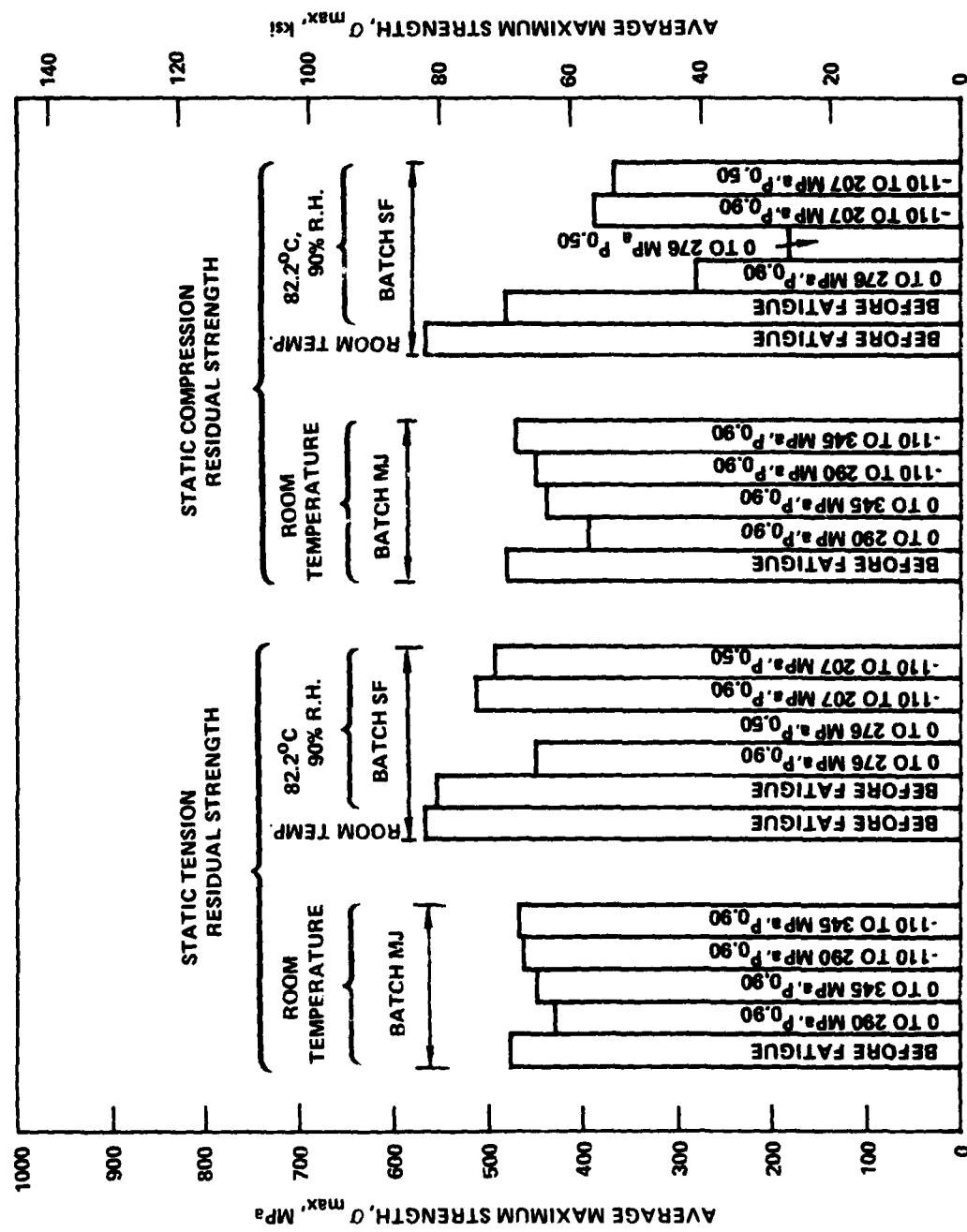
Figure 109. Histogram of Residual Strength Results for Un-notched Laminate 1 Coupons (Batch MJ is Ref. 1 Material, Batch SF is this material)
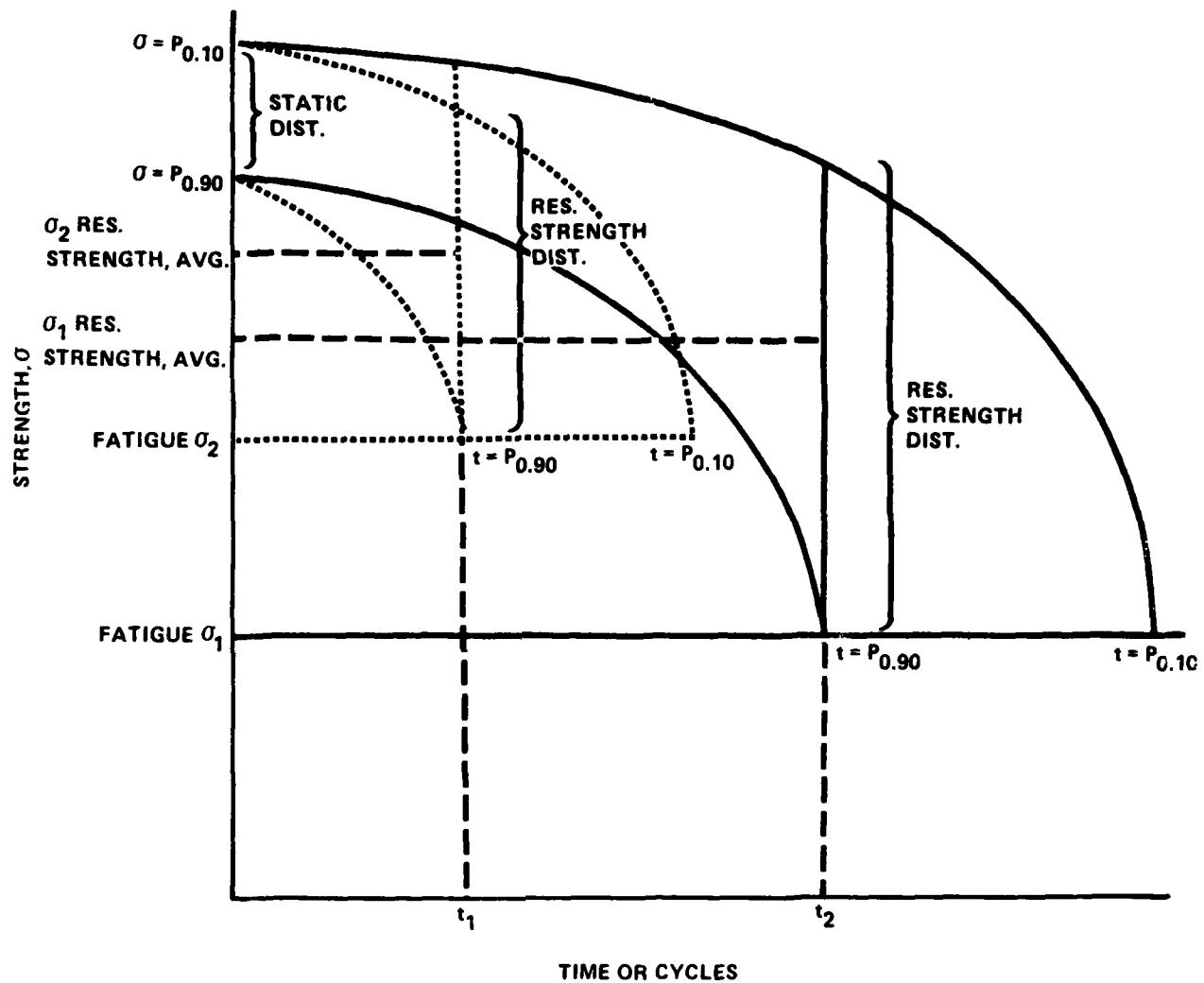
Figure 110. Idealized Graph of Strength Degradation with Time Under Fatigue Loading
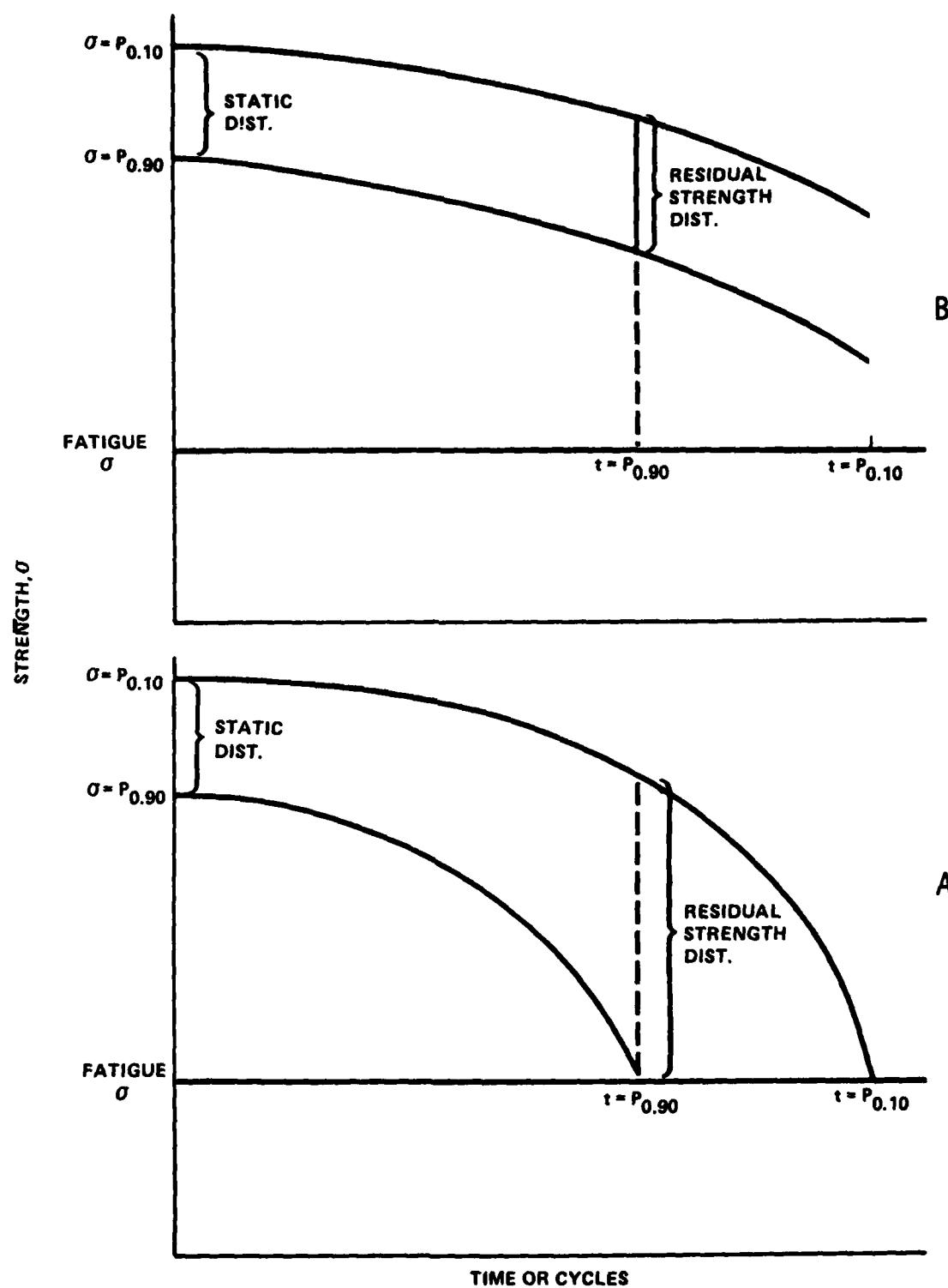
Figure 111.   Idealized Graphs of Strength Degradation:
A)   Equal Rank Order Assumption;
B)   Equal Rank Order Not Assumed

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coupons fatigue cycled at the lower stress level should clearly be lower than those fatigue cycled to the corresponding $P_{0.90}$ cycle life at the higher fatigue stress level. Likewise, the residual strength of coupons fatigue cycled to $P_{0.50}$ should be lower than those cycled to $P_{0.90}$. Both of these conclusions are supported by the data trends shown in Figure 109.

Procedures for analyzing residual strength data have usually assumed that there exists a simple one-to-one (equal rank) correspondence between a coupon rank in static strength and that in fatigue life. This assumption combined with the coupons observed strength degradation leads to the conclusion that the relationship between fatigue induced failures and static failures is similar to that shown in Figure 111A. However in this research program there was a large disparity between the distributions of the residual strength values and the corresponding maximum fatigue stress level. This observation is exemplified for the tension data in Table 41. The data of Table 41 indicates that the relationship between fatigue life and static tensile residual strength may be similar to that shown in Figure 111B rather than that commonly assumed as in Figure 111A. The fatigue induced damage which results in fatigue failure does not appear to have a direct effect on the tensile residual strength. This same result was previously observed for the room temperature residual strength tests (1).

The above indications are further supported by ranking the residual strength coupons based upon failure stress and comparing the resulting rank order to the observed estimated damage. This was attempted by using macro delamination extent as an estimate of fatigue induced damage. Observed damage was defined as being in one of three categories: 1) light, no delamination observable by eye or small amounts less than approximately 25 mm (1 in.); 2) medium, delamination on both sides extending from approximately 25 to 76 mm (1 to 3 in.) without going into several layers; 3) severe, delaminated from end to end, or nearly so, with delamination extending in between many plies.

Results of the correlation using all the data which was collected on fatigue induced damage prior to static failure is tabulated in Tables 42 to 44.

TABLE 41

RESIDUAL STRENGTH STUDY FOR UN-NOTCHED LAMINATE 1 COUPONS TESTED
AT 82.2°C (180°F) IN STATIC TENSION

Fatigue Stress Level, MPa (ksi)	Estimated Probability of Survival, P_s	Lowest Tensile Failure Stress MPa		Average Tensile Strength MPa	ksi
Static Tension	--	452	65.6	556	80.6
0 to 276(0 to 40)	0.90	382	55.4	452	65.5
0 to 276(0 to 40)	0.70	330	48.3	401	58.1
-110 to 207(-16 to 30)	0.90	436	63.3	513	74.4
-110 to 207(-16 to 30)	0.50	374	54.2	493	71.5

TABLE 42

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON

RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 1 COUPONS

Test Environment: 82.2°C(180°F), 90% R.H. Laboratory Air

Fatigue Loading: 0 to 276 MPa(0 to 40 ksi) No. of Cycles: 100,000

Estimated Amount of Delamination
(Strength in Rank Order)

| Tension Tests | | | Compression Tests | | |
Light	Medium	Severe	Light	Medium	Severe
73.4			67.2		
72.0			63.2		
		71.8	49.7		
71.5			46.2		
	71.0			43.5	
69.8			42.2		
69.3			41.5		
	69.1		41.5		
		68.9	41.0		
	68.8			40.0	
	67.2			39.2	
	65.3			39.1	
		64.2		38.1	
	61.1		37.9		
	59.1		37.8		
	58.0		37.4		
		56.4	35.3		
	55.4		32.4		
		52.1		25.2	
				23.1	
Average Values					
71.2	63.9	62.7	43.3	35.5	
	65.5			40.6	

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TABLE 43

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON
RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 1 COUPONS

Test Environment: 82.2°C(180°F), 90% R.H., Laboratory Air

Fatigue Loading: 0 to 276 MPa(0 to 40 ksi)
No. of Cycles: 300,000

Estimated Amount of Delamination
(Strength in Rank Order)

Tension Tests			Compression Tests		
Light	Medium	Severe	Light	Medium	Severe
74.1			37.8		
	71.9		37.1		
	69.6		37.0		
68.0			35.6		
	61.9			35.0	
	61.7				31.0
60.3				30.8	
	60.1		30.4		
		56.6		24.9	
	55.5			23.1	
	54.9				22.3
		54.5			22.2
	53.8	53.8			22.1
		53.8		20.4	
		51.9	20.3		
		49.1			19.8
		48.3			19.8
	36.8				18.7
					18.5
					16.5
Average Values					
67.6	58.5	52.6	33.0	26.8	21.1
58.1			26.5		

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TABLE 44

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 1 COUPONS

Test Environment: 82.2°C (180°F), 90% H.R., Laboratory Air

Fatigue Loading: -110 to 207 MPa (-16 to 30 ksi)
No. of Cycles: $17,7506 = P_{0.90}$

Estimated Amount of Delamination
(Strength in Rank Order)

Tension Tests		
Light	Medium	Severe
82.7		
81.0		
	80.2	
	79.2	
	78.6	
78.1		
77.5		
77.2		
77.0		
76.3		
74.6		
73.1		
72.6		
	72.3	
	71.7	
71.5		
	68.7	
67.1		
64.4		
63.3		
Average Values		
74.1	75.1	
74.4		

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These tables clearly show that the greater the amount of fatigue induced delamination the lower the average residual strength. This trend, while clearly identifiable, is not absolute since the data overlaps considerably. These results suggest to this investigator, that the fatigue induced damage has resulted in a relationship between static and fatigue distributions whose general nature is not strongly related to an equal rank hypothesis. Possibly, the correlation would be improved by conducting all residual tests at the same strain rate as that used for the fatigue tests. This may reduce the static tensile strength by as much as 10% [25]. Making such an adjustment would not restore the equal rank hypothesis nor would the fact be changed that the residual strength failure stresses for any one damage group is high compared to the maximum fatigue stress.

Some thoughts are here outlined to aid in our understanding of the residual strength results for un-notched laminate 1 coupons. When an un-notched quasi-isotropic laminate 1 coupon is subjected to constant amplitude fatigue loading, the principal form of induced damage is delamination between the $\pm 45^{\circ}$ plies. Under continued fatigue cycling, the delamination extends from the initiation region (or regions) both longitudinally and transversely and eventually extends into other plies. Coupon stiffness decreases by 15% or more due to lack of shear transfer.

Under tension-tension fatigue, the induced delamination damage does not result in breaking of the coupon into two pieces. However, because of the extent of degradation in coupon structural integrity and in stiffness change, a fatigue induced failure could be defined. Actual breakage of the coupon into two pieces does not occur until a "dominant flaw" develops. This failure occurs when, within some relatively small region, a crack transverse to the load begins to develop due to breakage of the 0° fibers. Once this dominant region of 0° fiber breakages occurs, propagation of the crack appears to be rapid and failure occurs in only a few cycles. The initial delamination region of damage and the rate of subsequent growth must be characterized statistically because the process appears random due to present and, most

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likely, future inadequacies of available non-destructive examination procedures. Likewise, determination of the region where the "dominant flaw" may occur is also, at present, difficult and thus, also appears random. Thermographic systems may help in this regard [26].

Under tension-compression fatigue loading, the induced damage and subsequent growth is quite similar to that described for tension-tension fatigue. However, unless the coupon is completely laterally restrained, failure occurs rather quickly after the delamination has propagated only over a relatively small region. The coupon may fail to sustain any compression load because the plies buckle laterally out of the load plane due to the loss on coupon structural integrity. This compression buckling condition necessitates termination of the test. If the lateral out-of-plane buckling is constrained by interference of a buckling support or end tab, the $0°$ plies fracture and coupon failure into two pieces occurs. This same failure mode occurs in those coupons which will not sustain significant compression load if they are driven into compression.

The above described damage initiation and growth due to the two types of fatigue loading allows explanations of the observed fatigue results to be inferred. We originally defined failure under T-T loading as a fractured specimen and under T-C loading the same way or as failure to sustain compression loading. The above discussion clearly implies that equal amounts of delamination could result in failure under T-C loading, but not under T-T loading. Therefore, T-T loading should, in general, lead to longer lives than under T-C loading. This result is observed for both the room temperature [1] and high temperature data when plotted on the basis of stress range.

Understanding the nature of the fatigue induced damage initiation and growth and subsequent failure leads to an improvement of our understanding of the residual strength results. Coupons which are fatigue loaded to a cycle life equivalent to a particular probability of survival have incurred various levels of delamination type damage. However, most likely, a "dominant flaw" region

has not yet developed. Therefore, the failure strength of coupons statically loaded to failure in tension will be generally reduced by the delamination damage, but their rank order will not be closely related to that which would have occurred if they were failed while under either T-T or T-C fatigue loading. If the fatigue loaded coupons are failed in static compression in a fully restraining fixture, their rank order would be distinctly different than which would have occurred under static loading. This is because the coupon rank order under static compression is dependent upon the extent of delamination. Under T-T loading, the development of the "dominant flaw" determines rank order more than total amount and extent of delamination. Under T-C fatigue loading, coupon rank order due to fatigue failure or static compression would be more closely related since both failures are principally dependent upon the extent of delamination.

The above considerations lead to the conclusion that when analyzing the effect of fatigue loading on subsequent residual strength, careful thought must be given to the nature of damage initiation, subsequent growth, failure mode and the relationship of the failure modes under different loading conditions. For the tensile residual strength data of this investigation, the rate of strength decrease relative to fatigue life is similar to Figure 111B. An exact equal rank relationship would result in the type of curve shown in Figure 111A. This assumption fails to consider the physical nature of fatigue induced damage and associated failure modes. The strength of coupons while under fatigue loading does not decay in the manner of Figure 111A, because this strength and the static residual strength are not the same things. The closest relationship between them occurs when the compression strength is reduced due to tension-compression fatigue loading. The results of the present investigation strongly suggests that the equal rank assumption is at best a approximation. The level of acceptable inaccuracy is dependent upon the particular application of the data.

Notched

In Tables 45 and 46 are given the residual strength test results for the notched laminate 1 coupons at room temperature and at 82.2°C (180°F), respectively.

TABLE 45

SUMMARY OF RESIDUAL STRENGTH TEST RESULTS FOR NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT ROOM TEMPERATURE IN LABORATORY AIR

Fatigue Stress Levels MPa / ksi	Probability of Survival, P_s	Equivalent Cyclic Life, Cycles	Weibull Parameters k	e	v	Correlation Coefficient, R	Average Notched Tensile Strength σ_{avg} MPa	ksi
Tension Test Results								
Before Fatigue	-	-	29.2 26.9	-0.06 0	41.8 41.9	0.9993 0.9814	284	41.2
0 to 234 0 to 34	0.90	34,830	22.6 21.0	-0.06 0	49.7 49.9	0.9995 0.9832	336	48.8
0 to 234 0 to 34	0.50	159,350	16.830 15.453	-0.19592 0	51.128 51.479	0.99835 0.98044	344	49.9
-110 to 152 -16 to 22	0.90	105,460	15.157 14.129	-0.11226 0	47.905 48.276	0.99885 0.98511	321	46.6
-110 to 152 -16 to 22	0.50	255,390	18.397 16.212	-0.0190 0	48.375 49.051	0.99982 0.99119	328	47.6
Compression Test Results								
Before Fatigue	-	-	13.9 13.2	-0.13 0	46.5 46.9	0.9987 0.9864	312	45.2
0 to 234 0 to 34	0.90	34,830	11.485 10.543	-0.29084 0	47.651 48.182	0.99710 0.97469	318	46.1
-110 to 152 -16 to 22	0.90	105,460	13.894 12.919	-0.1648 0	45.615 49.984	0.99826 0.98340	305	44.3
-110 to 152 -16 to 22	0.50	255,390	11.033 9.283	-0.57396 0	42.971 43.644	0.99428 0.95606	286	42.5

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TABLE 46

SUMMARY OF RESIDUAL STRENGTH TEST RESULTS FOR NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

Fatigue Stress Levels MPa ksi	Probability of Survival, P_s	Equivalent Cyclic Life, Cycles	Weibull Parameters k	e	v	Correlation Coefficient, r	Average Notched Tensile Strength σ_{avg}, MPa	ksi
Tension Test Results								
Before Fatigue	-	-	12.2 / 10.4	-0.45 / 0	40.5 / 41.0	0.9959 / 0.9744	270	39.2
0 to 193 0 to 28	0.90	27,970	15.8 / 14.3	-0.16 / 0	47.4 / 47.8	0.9986 / 0.9800	319	46.2
0 to 193 0 to 28	0.50	81,770	11.409 / 7.014	-2.4603 / 0	48.5366 / 9.729	0.9820 / 0.8678	321	46.5
-110 to 138 -16 to 20	0.90	8,680	13.544 / 11.197	-0.6069 / 0	41.976 / 42.438	0.9940 / 0.9430	281	40.7
-110 to 138 -16 to 20	0.50	19,340	31.299 / 25.596	-0.045874 / 0	43.057 / 43.468	0.9994 / 0.9497	294	42.6
Compression Test Results								
Before Fatigue	-	-	20.1 / 18.0	-0.12 / 0	40.8 / 41.1	0.9987 / 0.9766	276	40.0
0 to 193 0 to 28	0.90	27,970	10.283 / 7.961	-0.1670 / 0	38.731 / 40.049	0.9983 / 0.9598	261	37.8
0 to 193 0 to 28	0.50	81,770	7.451 / 6.487	-0.7235 / 0	38.658 / 39.373	0.9957 / 0.9835	254	36.8
-110 to 138 -16 to 20	0.90	8,680	12.604 / 11.971	-0.1087 / 0	39.860 / 40.214	0.9986 / 0.9822	266	38.6
-110 to 138 -16 to 20	0.50	19,340	13.497 / 11.699	-0.1487 / 0	37.171 / 37.856	0.9979 / 0.9698	251	36.4

This notched residual strength data is quite unlike the un-notched results. The average residual strengths of all tension tests were higher than the average for the coupons tested without prior fatigue, see Figure 112. This was true despite the fact that coupons did fail in fatigue prior to reaching the number of cycles equivalent to $P_{0.90}$ or $P_{0.50}$. In addition, the average values of the tensile residual strengths slightly increased after fatigue cycling to a life equivalent to $P_{0.50}$ compared to that determined at $P_{0.90}$. Under static compression loading, these trends did not occur except at room temperature after tension-tension fatigue, see Table 45. In all other cases, prior fatigue loading to a $P_{0.90}$ cyclic life did reduce the average static residual compressive strength which was further reduced after fatigue loading to a cyclic life equivalent to $P_{0.50}$. Under both tension and compression loading, the residual strength data did not display any consistent trends in scatter dispersion changes. The effect of temperature was to reduce somewhat the changes in residual strength relative to the unfatigued coupons compared to the results obtained at room temperature.

The tensile residual strength data for notched laminate 1 coupons does not display a wear-out type behavior while the compressive data was inconsistent. This result is similar with other work previously reported [27]. Three experimental results mitigate against the applicability of any simplified mathematical formulation for describing this notched residual strength data. First, under tension loading, the residual strength increased due to fatigue loading. Second, this increase in tensile residual strength is further enhanced by continued fatigue cycling. Third, fatigue failures occurred prior to reaching lives equivalent to $P_{0.90}$ or $P_{0.50}$ despite the fact that subsequent static tests resulted in an average residual strength higher than the original static strength. This strongly suggests that the extent of damage which occurred under fatigue loading has a different influence under static than under fatigue loading. This effect occurs despite the fact that the strain rate sensitivity of laminate 1 decreases the static strength rather than causing an increase [25].
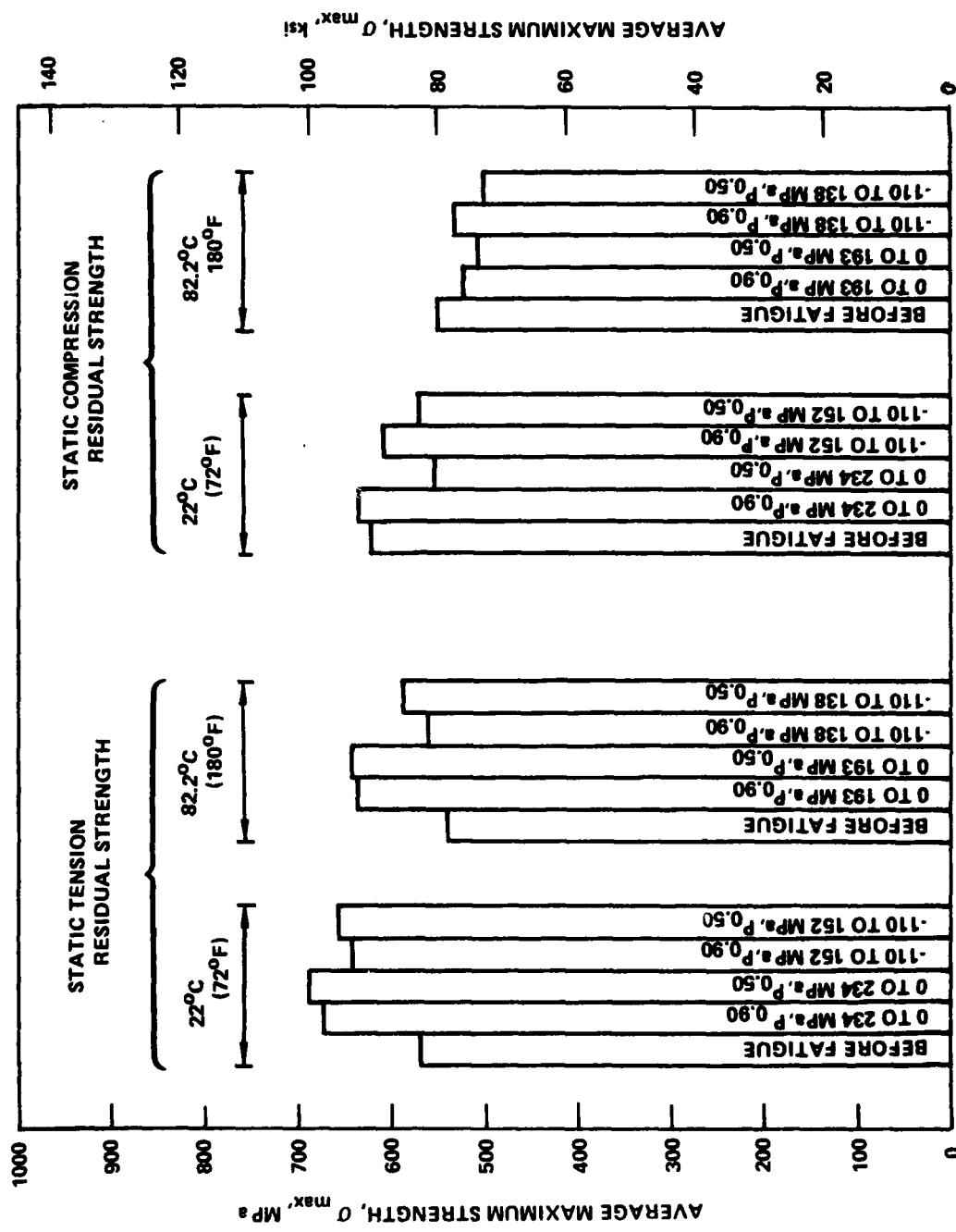
Figure 112. Histogram of Residual Strength Results for Notched Laminate 1 Coupon

The above results can be explained by considering the nature of the fatigue induced damage type and subsequent growth. Fatigue induced damage in these notched, quasi-isotropic coupons consists of delamination at or near the hole which propagates in a direction parallel to the loading direction. The effect of this damage form is to effectively reduce the stress concentration effect of the notch. Therefore, the residual strength of any coupon damaged by fatigue loading should be, and is, greater than the undamaged state. Failure, by fracture into two pieces, during fatigue loading occurs due to the development of a dominant flaw at the hole region. Therefore, the phenomenon arises where coupons can fail in fatigue, but remaining coupons have not yet developed dominant flaws and thus have increased strength. This effect of increasing residual static tensile strength continues for at least half of the coupons expected life under fatigue loading because the notch blunting process continues at least to that point in life. Therefore, we see that like the un-notched case, the tensile residual strength rank order of a coupon cannot be directly related to the fatigue distribution rank order. This is due to the fact the rank order under fatigue loading is dependent on the contribution of time to development of a dominent flaw while the residual strength rank order of remaining unfailed coupons is dependent upon the extent of notch blunting.

The situation for compression residual strength is somewhat different than for tension. The compression residual strength, similar to the un-notched case, is dependent upon the extent of delamination. Therefore, the fatigue induced damage can reduce the compressive residual strength. The rank order of their strengths should be similar to that which occurs in fatigue under T-C loading because such fatigue coupons fail due to delamination. This rank order similarity for compression residual strength should not be true for coupons fatigue loaded in tension-tension. Again, this is the same as the un-notched situation previously described.

7.2   Laminate 2 Residual Strength Results

The laminate 2 residual strength results obtained at 82.2°C (180°F) are summarized in Table 47 and in Figure 113. Tests were conducted on coupons

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TABLE 47

SUMMARY OF RESIDUAL STRENGTH TEST RESULTS FOR UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

Fatigue Stress Levels MPa / ksi	Probability of Survival, P_s	Equivalent Cyclic Life, Cycles[b]	Weibull Parameters[a] k	e	v	Correlation Coefficient, R	Average Ult. Stress MPa	ksi	Average Ult. Strain, ε_{avg} mm/mm in 50.8 mm	Average Secant Modulus to Failure, E_{sf} GPa	psi x 10[6]
Tension Test Results											
Before Fatigue	-	-	19.921 / 18.725	-0.2398 / 0	168.024 / 169.071	0.99928	1136	164.7	0.0112	101.4	14.7
0 to 689 0 to 100	-	2.5 x 10^5	14.059 / 11.820	-2.2241 / 0	157.850 / 159.349	0.99491 / 0.95673	1055	153.0	0.0102	104.1	15.1
0 to 689 0 to 100	-	10^6	12.321 / 10.946	-0.9143 / 0	145.479 / 147.295	0.99743 / 0.97923	963	139.6	0.0090	111.0	16.1
-207 to 552 -30 to 80	-	2.5 x 10^5	13.774 / 13.001	-0.5244 / 0	158.085 / 159.217	0.99873 / 0.98764	1051	152.5	0.0092	116.5	16.9
-207 to 552 -30 to 80	-	10^6	5.723 / 5.388	-0.6828 / 0	139.598 / 145.201	0.99687 / 0.97633	928	134.6	0.0088	116.5	16.9
Compression Test Results											
Before Fatigue	-	-	12.017 / 9.566	-2.5979 / 0	122.234 / 124.226	0.99216 / 0.94768	815	118.2	0.0098	83.4	12.1
0 to 689 0 to 100	-	2.5 x 10^5	13.111 / 10.881	-0.9393 / 0	110.303 / 112.074	0.99608 / 0.95410	740	107.3	0.0087	85.5	12.4
0 to 689 0 to 10	-	10^6	7.511 / 7.011	-1.0189 / 0	92.221 / 93.509	0.99680 / 0.98636	605	87.8	0.0071	85.5	12.4
-207 to 552 -30 to 80	-	2.5 x 10^5	7.720 / 6.955	-1.6029 / 0	101.918 / 103.711	0.99493 / 0.98005	658	95.4	0.0077	82.7	12.0
-207 to 552 -30 to 80	-	10^6	10.542 / 8.863	-0.3244 / 0	94.322 / 97.391	0.99783 / 0.95681	639	92.7	0.0077	84.1	12.2

a - First entry is 3-parameter, double logarithmic Weibull fit; second entry is classical 2-parameter Weibull fit

Figure 113. Histogram of Residual Strength Results for Notched Laminate 2 Coupons

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cycled to 2.5×10^5 or 1×10^6 cycles under tension-tension fatigue loading at 0 to 689 MPa (0 to 100 ksi) and under tension-compression fatigue loading at -207 to 552 MPa (-3C to 80 ksi). The residual strength results at 82.2°C (180°F) were significantly different than those previously obtained at room temperature [1].

At room temperature, despite fatigue failures, coupons which survived 10^6 fatigue cycles showed little observable damage [1]. However, those tested at 82.2°C (180°F) in this program, which survived 10^6 fatigue cycles, generally exhibited extensive outer ply shredding and delamination. This observed effect of the high temperature and moisture environment wa reflected in a significant drop in tensile residual strength of up to 20%. At room temperature, no effect on the tensile residual strength was observed [1]. The effect of the high temperature environment on the compressive residual strength was quite severe; 40% maximum reduction versus 15% at room temperature [1].

A summary of the results is that there was no observed effect of fatigue induced damage on the tensile residual strength at room temperature, but there was a significant effect at high temperature. he effect of fatigue induced damage on tensile residual strength at high temperature was greater at 1×10^6 fatigue cycles (equivalent to $P_{0.50}$) than at the lesser number of cycles of 2.5×10^5. Therefore, a wear-out type phenomenon is apparent in tensile residual strength at high temperature and not at room temperature. In both cases, fatigue failures occurred prior to obtaining the residual strength of unfailed coupons. At both high temperature and room temperature, the compressive residual strength decreased due to fatigue induced damage. The more severe effect was observed at high temperature. The larger amount of fatigue induced damage incurred after 1×10^6 fatigue cycles resulted in lower compressive residual strengths than that which was incurred after 2.5×10^5 cycles.

The results of the laminate 2 residual strength study can be explained in a manner similar to that described for the laminate 1 un-notched and notched results. Fatigue loading induced damage in laminate 2 coupons predominately

consists of delamination and 0° fiber fracture of fiber bundles in the two outer surface, 0° plies. An extensive amount of such damage could be defined as fatigue failure. However, in this program, rank failure order of the coupons due to fatigue loading was determined by fracture of the coupon. Fatigue failure life is thus determined by the transverse fracture of a large number of 0° fibers in some specific region or regions. Essentially, this is a dominant flaw problem. Rank order of the tensile residual strength coupons is not based upon the same dominant flaw as in fatigue failure rank order because, generally, such a region has not yet developed in residual strength coupons which did not fail in fatigue. The tension failure strength of an unfailed fatigue coupon, while dependent upon the amount of fatigue induced damage, is not failing due to the same kind of damage as causes the fatigue failure nor even necessarily damage in the region of the coupon. Therefore, the rank order of the tensile residual strength coupons is not directly related to the fatigue rank order. Further, the tensile residual strength should always be significantly higher than the maximum fatigue stress level.

These expected effects are clearly shown in Tables 48 to 51 which compare the estimated amount of predominant damage to tensile residual strength rank order. As for the un-notched laminate 1 results, the data supports the assumption that the more severe the fatigue induced delamination damage, the lower the tensile residual strength. However, this trend is difficult to discern for coupons subjected to tension-tension fatigue loading and not particularly strong for those subjected to tension-compression loading. Compressive residual strength did not show any clear dependence of rank order or extent of fatigue induced damage, see Tables 48 to 51. The effect of delaminated bundles of outer surface ply 0° fibers was significantly reduced by the restraint of the test fixture. Therefore, the compressive residual strength results do not appear to rank in an order related to that observed due to fatigue.

TABLE 48

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON
RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 2 COUPONS

Test Environment: 82.2°C(180°F)   <u>Fatigue Loading:</u> 0 to 689 MPa(0 to 100 ksi)
90% R.H., Laboratory Air   <u>No. of Cycles:</u>   250,000

Estimated Amount of Damage
(**Strength** in Rank Order)

Tension Tests			Compression Tests		
Light	Medium	Severe	Light	Medium	Severe
166.4			131.6		
	165.9				119.8
165.4				118.8	
163.2			118.0		
162.6			115.0		
		161.8	113.5		
		159.9	112.2		
158.9				110.7	
158.7			110.6	110.6	
158.5					110.5
157.1			110.4		
157.0			104.5		
156.1			104.2		
154.5			103.7		
151.6			99.4		
148.0					96.2
147.9		146.4	94.9	94.9	
143.2			94.5		
	137.1			94.7	
129.5			92.0		
115.3					
Average Values					
152.7	151.5	156.0	107.5	105.7	108.8
153.0			107.3		

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TABLE 49

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON

RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 2 COUPONS

Test Environment: 82.2°C(180°F) 90% R.H., Laboratory Air

Fatigue Loading: 0 to 689 MPa(0 to 100 ksi) No. of Cycles: 10^6

Estimated Amount of Damage
(Strength in Rank Order)

Tension Tests			Compression Tests		
Light	Medium	Severe	Light	Medium	Severe
	161.1		102.5		
		153.8			102.3
	152.2		100.5		
		152.1			99.8
		150.8	98.9		
		150.6	97.0		
	147.0				95.2
		146.1	87.1		
	144.6		87.0		
135.1	135.1			85.8	
131.2					84.7
	130.3				81.1
		128.4		76.1	
		127.1	72.8		
		112.2		71.2	
			62.3		
Average Values					
133.2	1.51.2	136.2	88.5	77.7	92.6
139.6			87.8		

TABLE 50

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON

RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 2 COUPONS

Test Environment: 82.2°C(180°F) 90% R.H., Laboratory Air

Fatigue Loading: -207 to 552 MPa(-30 to 80 ksi) No. of Cycles: 2.5×10^5

Estimated Amount of Damage
(Strength in Rank Order)

	Tension Tests			Compression Tests	
Light	Medium	Severe	Light	Medium	Severe
169.8				120.6	
166.7					117.1
163.9	163.9		115.8		
163.4			108.4		
162.2			105.8		
	160.7				105.5
158.5			104.4		
158.3			103.2		
	156.2		100.6		
	152.7		99.5		
	149.3			97.7	
	146.4		93.9		
146.3			93.4		
		142.3		84.3	
		140.9	92.9		
136.5			82.3		
124.1			76.5		
			73.8		
			72.2		
		Average Values			
155.0	154.9	141.6	93.8	100.9	111.3
	152.5			95.4	

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TABLE 51

ESTIMATED FATIGUE LOADING INDUCED DAMAGE AND ASSOCIATED COUPON
RESIDUAL STRENGTH FOR UN-NOTCHED LAMINATE 2 COUPONS

Test Environment: 82.2°C (180°F) 90% R.H., Laboratory Air

Fatigue Loading: -207 to 552 MPa(-30 to 80 ksi) No. of Cycles: 1×10^6

Estimated Amount of Damage
(Strength in Rank Order)

Tension Tests			Compression Tests		
Light	Medium	Severe	Light	Medium	Severe
156.9	163.0				106.3
				103.0	
	151.0		97.1		
		132.0	90.0		
					86.0
	121.4				
	112.0			85.0	
		105.6	81.5		
Average Values					
156.9	136.9	118.8	89.5	94.0	96.2
134.6			92.7		

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SECTION VIII

SUMMARY

8.1 OBSERVATIONS AND CONCLUSIONS

This subsection summarizes specific experimental observations and con-
clusions which pertain to narrow width coupons of a type similar to that used
in this research program. The numbers in parenthesis at the end of each item
reference the particular subsection of the report which provides experimental
support.

Environmental Conditioning

- Un-notched coupons were tested at three different environmental
  conditions: $22°C(72°F)$, ~ 0.4% moisture; $82.2°C$ $(180°F)$, ~ 1.3%
  moisture; and $82.2°C(180°F)$, ~ 1.7% moisture. (4.0)

- Notched coupons were tested under the following environmental
  conditions: $22°C$ $(72°F)$, ~ 0.4% moisture; $82.2°C$ $(180°F)$, ~ 1.5%
  moisture; and $82.2°C$ $(180°F)$, ~ 1.7% moisture. (4.0)

- The two different moisture levels at $82.2°C$ $(180°F)$ are believed to
  be due to lamina sorption of water into environmentally induced
  matrix cracks. (4.0)

Static

- Scatter in un-notched, room temperature, static tension properties
  of this graphite/epoxy material was found to be significantly reduced
  by accounting for line discontinuity defects. (5.1)

- Batch to batch variation in laminate tension properties was found to be greater than 15%. (5.1)

- The effect of a hole on the quasi-isotropic static tension properties was well approximated by the "Point Stress Criteria" of Nuismer and Whitney [22]. (5.1)

- The effect of high temperature ($82.2°C$ ($180°F$)) and moisture content (1.3%) on the un-notched static tension properties of both laminates was not statistically significant. (5.5)

- The primary effect of the high temperature and moisture content on the un-notched static compression properties of both laminates was a 15 - 20% decrease in characteristic life and in average strength. (5.5)

- Notched static properties were affected by the high temperature and moisture content as seen by changes in data dispersion and/or characteristic life. (5.5)

- The effect of strain rate on ultimate strength was found helpful in explaining first cycle fatigue failures of laminate 2 coupons. (5.6)

Fatigue

- Significant differences in fatigue failure modes were observed. (6.0)

- Failure modes of coupons tested at $82.2°C$ ($180°F$), 90% R.H. were the same as those tested at room temperature. (6.0)

- Stress-life results at room temperature were not significantly affected by batch to batch material variations. (6.2)

- For laminate 1 notched or un-notched coupons on a maximum stress basis, the T-C loading reduced fatigue life below that observed for T-T loading. (6.2)

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- The fatigue life of laminate 1 notched coupons was always lower than un-notched. (6.2)

- The effects of the high temperature and humidity environment was to decrease the fatigue lives of un-notched and notched laminate 1 coupons as compared to room temperature results, by approximately a factor of 3 for un-notched coupons and by 10 for notched coupons. (6.2)

- The fatigue life of un-notched laminate 2 coupons was reduced at high temperature and humidity as compared to room temperature. (6.2)

- For un-notched laminate 1 coupons at high temperature and humidity, scatter in fatigue life was $\sim$ 1 to 1 1/2 orders of magnitude. (6.3.1)

- The higher the moisture content of un-notched laminate 1 coupons the lower the average fatigue life. (6.3.1)

- Except at stress levels near the ultimate static strength, notched laminate 1 coupons exhibited a fatigue life scatter of $\sim$ 1 to 1 1/2 orders of magnitude. (6.3.1)

- The high temperature and humidity environment significantly affected the fatigue properties of un-notched laminate 2 coupons. (6.3.2)

- No fatigue threshold at less than 10^7 cycles was observed for un-notched laminate 1 coupons. (6.4)

Residual Strength

- The residual strength of un-notched coupons of both laminates was found to decrease due to fatigue loading at high temperature and humidity. (7.1, 7.2)

- Notched laminate 1 coupons exhibited an increase in tensile residual strength at both room temperature and high temperature. (7.1)

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- A strong coupling between failure modes under static and fatigue loading was not observed. (7.0)

- An equal rank order relationship between the static residual strength and fatigue life distributions was not observed for laminate 2 coupons (7.2) and found to have a low correlation for laminate 1 coupons. (7.1)

8.2 DESIGN CONSIDERATIONS

This research investigation has brought to mind several specific considerations which are believed to be pertinent to users of graphite/epoxy composite materials. These considerations are: 1) The dependence of failure modes on local type and geometry; 2) the practical importance of a high temperature and humidity environment; 3) the nature and extent of scatter in static and fatigue data; and 4) the nature of damage initiation and growth. Each of these considerations are surveyed in this subsection.

8.2.1 Failure Modes

The result of this investigation integrated with the previous related research effort [1] has led to an awareness of the effect of various types of uniaxial loading on subsequent failure modes in both notched and un-notched coupons.

- As previously reported [28], the presence of a notch changes and focuses the dominant failure modes as compared to un-notched coupons. This notch dominance is true for both static and fatigue loading. This fact may drastically change the nature of any mathematical formulation for predicting fatigue life, static strength distribution, or the relationship between a coupon test result and structural components.

- For un-notched coupons, fatigue life is dependent upon the apriori definition of failure. This apparently obvious observation is important because fracture occurs in a coupon under tension-compression loading soon after delamination begins, but usually does not until

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considerably later if under tension-tension loading. This is due to the fact that under T-C loading, delaminated ply regions buckle while they do not under T-T loading. Therefore, defining fatigue life as a fixed extent of delamination or loss in stiffness completely alters a comparison between T-C and T-T loading as opposed to selecting fracture into two pieces as a life criteria. In addition, the relationship between fatigue life distribution and the static tension and compression strength distributions is greatly altered (see Section 7.0) by the selected definition of a fatigue failure. The problem is complicated by the fact that failure under static compression loading [2] or life under T-C fatigue loading [29] are dominated by the nature of the exterior constraints against buckling.

The implications of these considerations on failure modes is that strength and life analysis/prediction formulations must carefully take them into account accepting thereby the imposed limitations. For instance, life prediction formulations for un-notched coupons under T-C loading will not be pertinent if constraint systems are changed unless the effect of the constraint system can be analyzed separately. Similarly, strength degradation models should account for changes induced by the selected definition of fatigue failure.

8.2.2 Effect of Environment

This research study emphasized characterization of the effect of a high temperature (82.2°C (180°F))and high humidity (90%) environment, both during conditioning and testing, on notched and un-notched fatigue properties. An overall observation of design relevance is that no major surprises were observed. Although degradation in properties occurred, failure modes and the general senario of damage initiation and growth did not change. The relationship between type of loading and associated induced damage also was not altered. The principal observations were that the level of moisture content could: 1) be significantly affected by temperature perturbations between room temperature and 82.2°C (180°F); and 2) significantly affects fatigue

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life. Hypothetically, these results are caused by different amounts of
matrix cracking. This is supported by the work of other investigators [19].

8.2.3 Data Scatter

A remark which is often made is that composites have large scatter in
their static tension and fatigue properties. Because of this, the question
of scatter was investigated in this program (see Sections 5.1, 5.6 and 6.3.1).
The question as to how much data dispersion is expectable is important
because, at present, structural design using composites is based upon "A"
and "B" type statistical allowables. These 95% and 90% confidence limits are
naturally determined by the extent of data dispersion. Historically for
metals these confidence limits have been based upon the apparent intrinsic
material variability. This implies, for composites, the removal of variations
due to environment, moisture content, mechanical loading and history, and
manufacturing defects. In essence, the sources of scatter need to be identified
and those removed which can be discounted for by typical design procedures.
In the case of the un-notched coupons of laminate 1, this can be accomplished
to a great extent for certain properties.

For static tensile properties of un-notched laminate 1 coupons, the
results of Section 5.1 showed that if the effects of environment and moisture
content are removed (similar to environment and corrosion for metals) the
coefficient of variation (COV) within a single batch of material is reduced
to approximately 6% and the Weibull coefficient k (or α) increased to
approximately 20. Panel to panel variation is about 2%, similar to the
variation in properties found in different ingots of metallic materials. If
the effect of line discontinuity [30] is removed (see Table 15) the COV decreased
to 3.8% and k increased to 34. These variations begin to approach those
obtained for many metallic materials.

In the case of tension - tension fatigue loading of un-notched laminate 1
coupons, the results of Section 6.3.1 and references 1 and 30 indicate that
if environment, moisture content, batch variation, and line discontinuity
effects are removed, the scatter in fatigue life is significantly reduced.

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This encouraging result is supportive of that found for the laminate 1 static tension data.

The implication of these observations is that saying scatter is large in graphite/epoxy composites is a generalized statement which ignores differences in laminate properties and does not allow for sources of variation which are normally and correctly excluded when considering intrinsic properties of other materials. Therefore, the suggestion is made that future evaluations of graphite/epoxy properties should eliminate variables normally accounted by other means and thus not bias the nature of intrinsic material variability.

8.2.4 Damage Initiation and Growth

The results of this investigation and that conducted previously has led to a qualitative description of the damage initiation and growth process in graphite/epoxy composites. These thoughts are not necessarily new in the technical community, but need to be stated. The delineation of a point of view as to the cause of failure in fatigue is as follows:

1. Matrix microcracks occur (these exist initially by manufacture or environmental conditioning or are load induced).

2. Number of microcracks increase as load cycles increases.

3. Number of microcracks saturate.

4. Dominant mechanism changes to delamination (large cracks).

5. Delamination extends.

6. Fibers fracture in many diverse regions.

7. Fracture occurs at a statistically dominant flaw region.

This description of the fatigue loading induced damage initiation and growth process is believed to be generally applicable. Details are modified by the specifics of the particular layup, loading condition, and such geometrical changes as notches. Based upon the above described point of view on damage growth and initiation, several inferences can be drawn which

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relate the three previous discussed topics of this subsection. The inferences are:

1. There exist three principal damage mechanisms:
   a. Microcracks
   b. Delamination
   c. Fiber breakage

2. Stiffness decreases with time.

3. Fatigue life depends on the apriori definition of failure.

4. Normal and interlaminer shear ply stress determine:
   a. Location of microcracks
   b. Location of delamination
   c. Relative dominance of the three mechanisms

5. High moisture and temperature reduce fatigue life due to matrix plasticity and induced microcracks.

The first two inferences are self explanatory and the third item was previously discussed. Item four refers to the concept that laminate ply analysis should allow quantitative insight into which mechanisms dominant fatigue life for different laminates and loading conditions. The last item relates to the supposition that delamination begins after a specific extent of microcracking has occurred. Thus, if that microcracking exists prior to fatigue loading, fatigue life will be reduced as discussed in Section 6.3.1. The other major effect of high moisture and temperature is to reduce the shear resistance and increase local and global buckling instability.

8.3 RESEARCH RECOMMENDATIONS

Based on the results of this investigation, the following recommendations for failure research endevors are suggested:

* Determine the effect of notches in other laminate configurations.

- Delineate the mechanical response of wider and longer coupons and compare to narrow coupons.

- Extend analytical and experimental investigations into the phenomenalogical characteristics of damage initiation and growth for developing strength and life prediction models.

- Develop analytical life prediction models which account for the specific load and restraint configurations.

- Determine the relationship between coupon experimental data and full scale structural components.

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13

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APPENDIX A
T300/934 GRAPHITE/EPOXY LAMINATE AND
TEST SPECIMEN FABRICATION PROCEDURE
AFML Contract F33615-77-C-5045

1. Material Storage - All material shall be stored in sealed moisture-proof
bags in refrigerators maintained at -18 ± 5°C (0 ± 10°F). Storage time
shall not exceed six months.

2. Open Time - All material shall be laid up and cured within a total
cumulative time of 72 hours out of refrigerators. Material shall be
removed from refrigerators for at least one hour before removal from
covering bag.

3. Receiving Tests - Each batch of prepreg shall be sampled and tested in
accordance with Lockheed Material Specification C-22-1379/111.

4. Tool and Caul Plates for Curing - All tool plates used for curing lami-
nates shall be aluminum. Thickness of the caul plate shall be 12.7 mm
(0.500 in.) with a tolerance of ± 0.08 mm (± 0.003 in.), flat and paral-
lel. Caul plates used on top surface of laminate under the vacuum bag
shall be aluminum sheet (1.62 mm (0.064 in.) standard thickness).

5. Layup Procedure - Panels shall be laid up using 305 mm (12 in.) wide
pre-preg graphite/epoxy (T300/934) tape as the base material. Tape shall
be laid with a gap tolerance of 0 to 0.8 mm (0 to 0.031 in.). A check-
off system shall be used by the lay-up operator to assure proper orienta-
tion of the tape edge (within ± 2° of an oriented template) and stacking
sequence of each ply in the laminate. All panels shall be laid up over-
size to allow for 25.4 mm (1.0 in.) trim minimum on all edges of the
panel to avoid edge taper and resin content variables of panels as lam-
inated.

A-1

Panels shall be approximately 915 x 122 mm (36 in. x 48 in.) in size. Figures 1A and 2A show the detail of the tape and ply geometry for laminate 1 and laminate 2 panels, respectively.

6. Bleeding and Bagging Procedure - The bleeding and bagging materials used for curing laminates 16 plies thick shall be as listed in the following sequence starting from the surface of the caul plate:
    (1) Release film (Teflon)
    (2) Two plies Mochburg CW1850 Bleeder paper
    (3) One ply of porpus Teflon-coated glass cloth (duPont Armalon)
    (4) Graphite/epoxy laminate (Laminate 1 or 2)
    (5) One ply porous Teflon-coated glass cloth (duPont Armalon)
    (6) Two plies Mochburg CW1850 bleeder paper
    (7) Release film (Teflon)
    (8) Caul plate (aluminum 1.62 mm (0.064 in.) thick).
    (9) Glass boat cloth (vacuum distribution)
    (10) Nylon bag (Vac-Pac 0.076 mm (0.003 in.)thick)

    The nylon bag shall be sealed to the cure plate with sealing putty (Presstite No. CS12-4). The bag seal and bag shall be carefully checked for leaks under vacuum before the cure cycles are started.

7. Cure Proceedure - The thermocouple shall be placed on the caul plate adjacent to the laminate and the complete time-temperature history of each laminate monitored and recorded on a strip chart. The cure cycle used for T300/934 material shall be as follows:
    (1) Apply full vacuum 88-98 x 10^3 Pa (26-29 in.Hg)
    (2) Raise temperature to 121°C (250°F) at average of 1-2°C (3-4°F) per minute
    (3) Dwell at 121°C (250°F) for 15 minutes with vacuum pressure
    (4) Apply 0.69 MPa (100 psi) pressure plus vacuum and hold at 121°C (250°F) for 45 minutes
    (5) Raise temperature to 177°C (350°F) at 2-3°C (3-5°F) per minute
    (6) Hold at 177°C (350°F) and 0.69 MPa (100 psi) plus vacuum for 2 hours

A-2

(7) Cool to 82.2°C (180°F) under vacuum and pressure while recording cool-down rate

(8) Cool to 65.6°C (150°F) under vacuum only while recording cool-down rate.

8. <u>Resin Content and Voids</u> - The average resin and void content of each panel fabricated shall be determined. Void content shall be 2.0% max. by volume.

9. <u>Non-Destructive Inspection</u> - Three 0.05 mm (0.002 in.) thick Teflon pads of 3.175 mm (0.125 in.), 6.35 mm (0.25 in.), and 12.7 mm (0.50 in.) diameter shall be placed in the center section of each panel. Each panel shall be inspected using ultrasonic C-scan techniques. Results for known teflon pads within each panel shall be compared to an NDI reference panel standard containing known teflon pads at specified depths and of specified sizes as shown in Figure 3A. The adhesive used shall be American Cyanamid Co. FM-400 film, 1.90-mm (0.075 in.) thick, conforming to Lockheed Specification LCM 30-1085 Type II, Grade A.

Coupons shall be placed into a bonding fixture with spacers in between each coupon and glass tabs with associated adhesive above and below each end of the group of coupons. The tab stock end coupon fixture assembly shall be bagged and cured in an autoclave at 121°C (250°F) for one hour with a pressure 0.34 MPa (50 psi) plus vacuum. Coupons which are attached to each other after tabbing shall be separated by dry cutting of the connecting tab stock material.

10. <u>Panel and Coupon Identification</u> - All panels and coupons shall be clearly marked before and after application of tabs to indicate the bag side of the graphite/epoxy laminate as originally cured. Panels shall be identified with a number including material code and autoclave run number. Coupons shall be identified with panel number from which cut and dash numbers.

Example: ILY 556-1A

Coupons shall be numbered consecutively as they are cut from panels to indicate relative location in the panel, see Figure 4A.

11. Machining of Coupons - Coupons of the configurations shown in Figures 5A and 6A shall be machined from each panel as per Figure 4A. Coupons shall be machined dry using a 152.4 mm (6 in.) diameter, 40 tooth carbide cutter at 250 ± 10 rpm and at a feed rate of 304.8 ± 25.4 mm/min (12 ± 1 in./min). Holes shall be drilled using diamond drills and low feed rates which prevent any subsurface cracking of the type shown in Figure 7A-a such that the final hole surface appears as in Figure 7A-b.

12. Fabrication and Bonding of Glass Fabric/Epoxy Grip Tabs - Grip tab sheet material shall be fabricated by laminating eight plies of 1581 glass fabric/epoxy to make a laminate 1.65-1.78-mm (0.065-0.070 in.) thick. The material to be used is Fiberite Corp. MXB-7701/1581 glass fabric/ epoxy prepreg conforming to Lockheed material specification LCM C22-1032/ 131. This material is to be cured at 121°C (250°F) for one hour under a pressure of 0.34 MPa (50 psi) plus vacuum.

The glass fabric/epoxy laminate shall be cut into 57-mm (2.25 in.) wide strips to be located on graphite panels in panels in preparation for bonding as shown in Figure 4A. After all preliminary machining is done, glass tabs shall be thoroughly cleaned by wiping with methyl-ethyl-ketone solvent.

13. Performance Requirements - Laminate panels shall be rejected if review of fabrication records reveals that prepreg did not meet Item 3 and laminates did not meet Items 8 and 9 of this fabrication procedure. In addition, finished coupons shall be measured for width in four (4) places and for thickness in eight (8) places as per Figure 8A. Coupons shall be re-jected if all width measurements are not 22.22 ± 0.07-mm (0.875± 0.003 in.) and if thickness is not within ± 0.05-mm (± 0.002 in.) of the aver-age of eight thickness measurements.
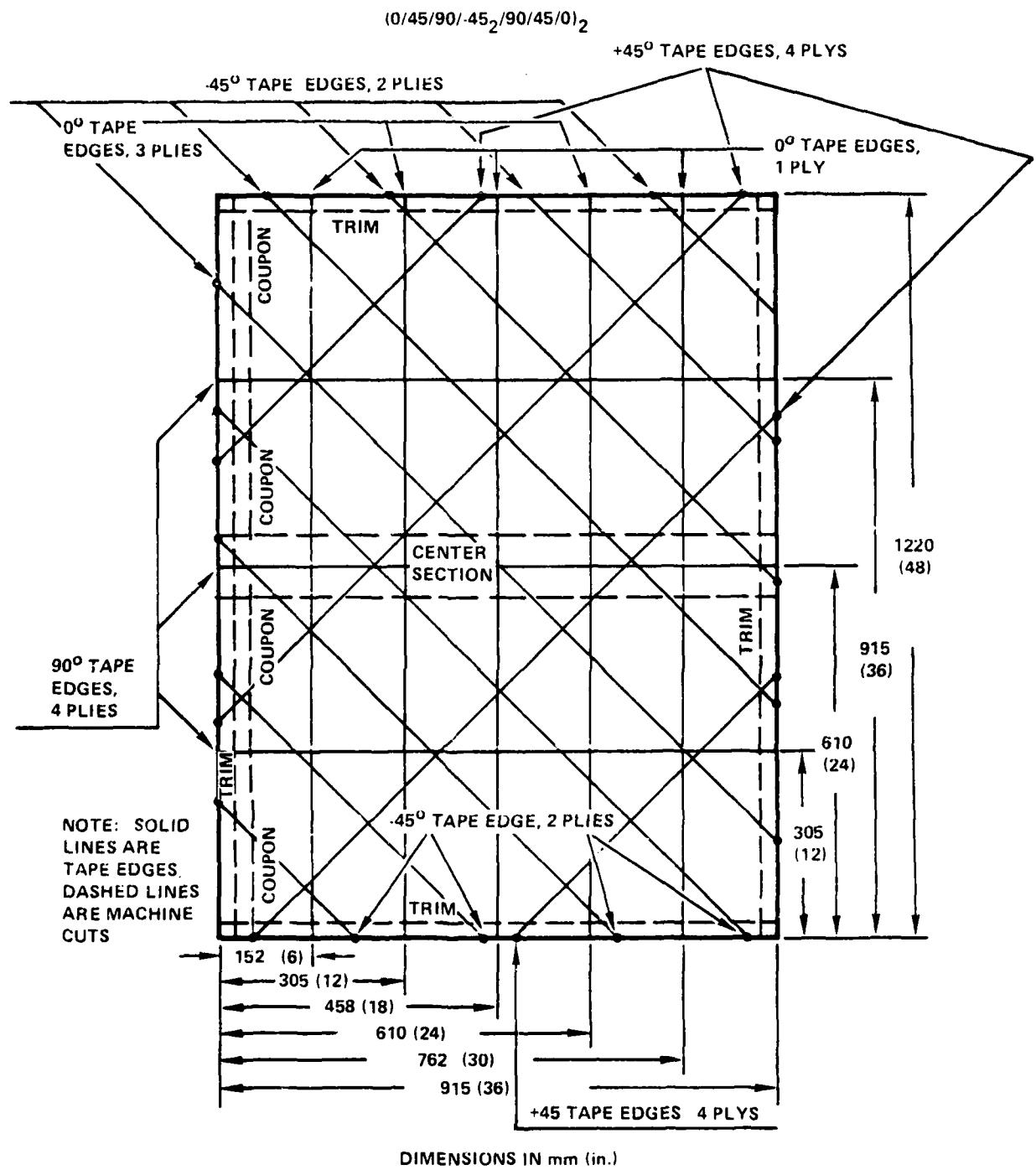
Figure 1A. Tape and Ply Geometry at Laminate 1 Panels

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$(0/45/0_2/-45/0_2/45/0_2/-45/0)_S$
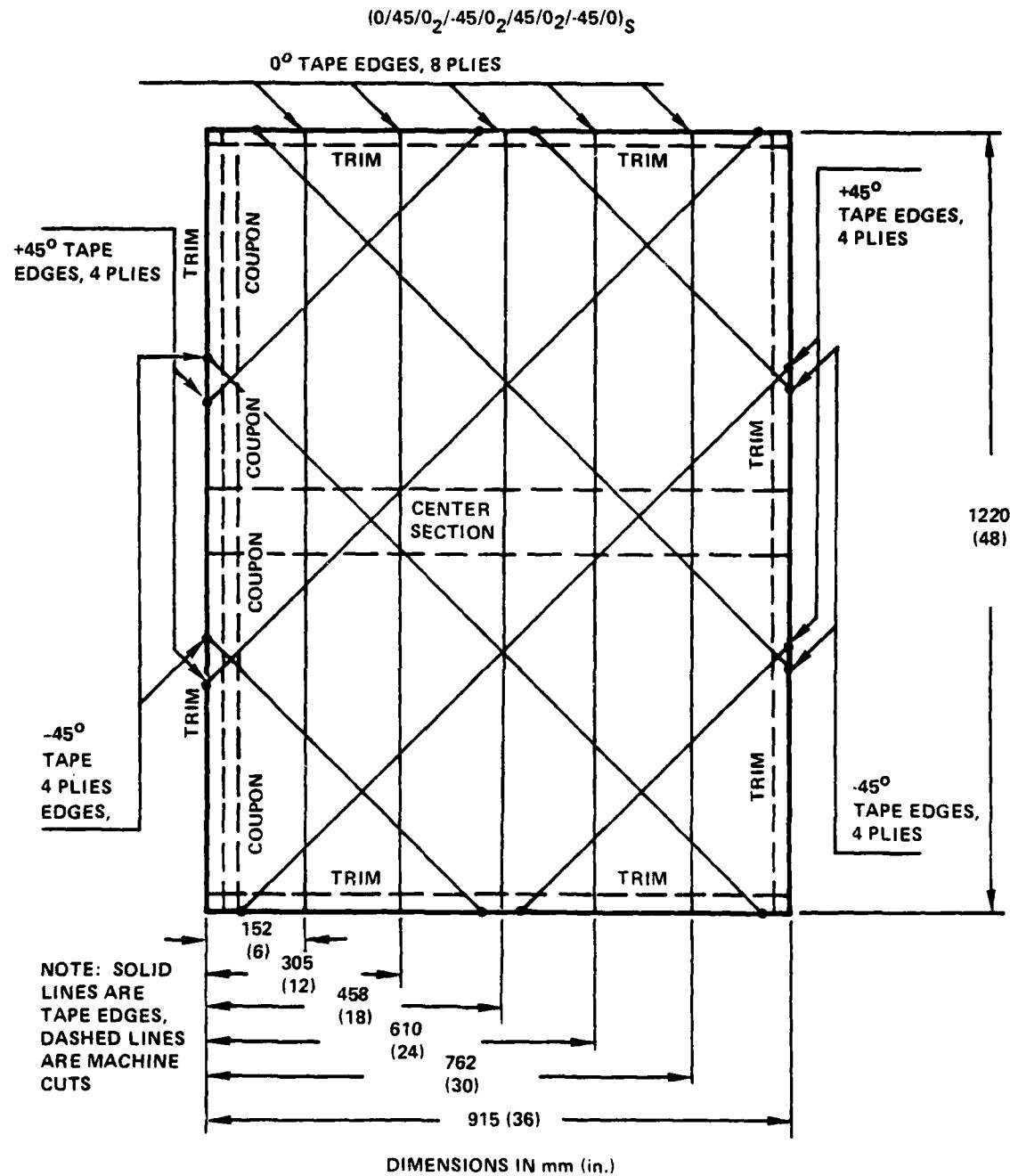
Figure 2A. Tape and Ply Geometry of Laminate 2 Panels

A-'

3.175 mm
(0.125 in.)

0.05 mm (0.002 in.)
2 MIL TEFLON FILM PLACED
AT 1/4 DEPTH EXCEPT AS
NOTED AT 1/2 DEPTH

12.7 mm
(0.50 in.)
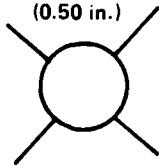
3.175 mm
(0.125 in.)
HALF DEPTH
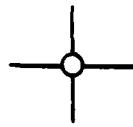
25.4 mm
(1.0 in.)
DBL
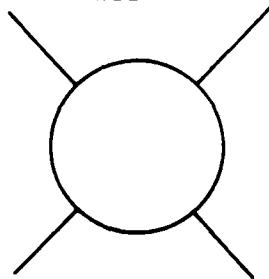
12.7 mm
(0.50 in.)
HALF DEPTH
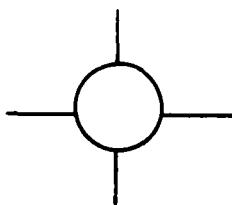
6.35 mm
(0.25 in.)
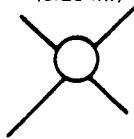
6.35 mm
(0.25 in.)
HALF DEPTH
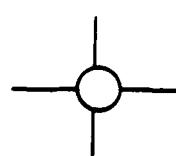
25.4 mm
(1.0 in.)
SINGLE
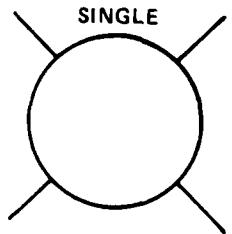
Figure 2A.   NDI Reference Standard for Graphite/Epoxy Panels

Figure 4A. Identification of Panels and Coupon Locations

ALL DIMENSIONS IN MILLIMETERS

[9] SPECIMENS TO BE FLAT OVER THE ENTIRE 267-MM (10.5-IN.) LENGTH WITHIN 0.25-MM (0.01-IN.)

[8] TAB EDGES TO BE PARALLEL TO SIDES OF SPECIMEN WITHIN 0.025-MM (0.001-IN.) OVERHANG NOT TO EXCEED 3.8-MM (0.003-IN.)

[7] THE TAB AND SPECIMEN BONDING SURFACES TO BE THOROUGHLY SOLVENT CLEANED USING METHYL-ETHYL-KETONE PRIOR TO BONDING. A 350°F CURING ADHESIVE IS TO BE USED AND MUST COVER ENTIRE SURFACE UNIFORMLY.

[6] SPECIMENS TO BE CUT DRY. MACHINED SURFACES TO BE RMS 50 OR BETTER. NO EDGE DAMAGE OR FIBER SEPARATION SHOULD BE VISIBLE UNDER 10X MAGNIFICATION.

[5] MEASURE SPECIMEN WIDTH 4 PLACES. WIDTH MUST NOT VARY BY MORE THAN 0.102-MM (0.004-IN.)

[4] SPECIMEN WIDTH TO BE 22.225±0.127-MM (0.875±0.005-IN.)

[3] MISMATCH OF TABS FROM SIDE TO SIDE NOT TO EXCEED 0.25-MM (0.01-IN.)

[2] TABS TO BE CUT FROM AN 8 PLY LAMINATE FABRICATED FROM PREPREG OF 1581 GLASS FABRIC IN A 350°F CURING EPOXY.

[1] SPECIMEN THICKNESS TO BE WITHIN ±0.08-MM (±0.003-IN.) OF THE AVERAGE OF 8 THICKNESS MEASUREMENTS.

Figure 5A.   Unnotched Composite Test Specimen

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ALL DIMENSIONS IN MILLIMETERS

⑨ SPECIMENS TO BE FLAT OVER THE ENTIRE 267-MM (10.5-IN.) LENGTH WITHIN 0.25-MM (0.01-IN.)

⑧ TAB EDGES TO BE PARALLEL TO SIDES OF SPECIMEN WITHIN 0.025-MM (0.001-IN.) OVERHANG NOT TO EXCEED 3.8-MM (0.003-IN.)

⑦ THE TAB AND SPECIMEN BONDING SURFACES TO BE THOROUGHLY SOLVENT CLEANED USING METHYL-ETHYL-KETONE PRIOR TO BONDING. A 350°F CURING ADHESIVE IS TO BE USED AND MUST COVER ENTIRE SURFACE UNIFORMLY.

⑥ SPECIMENS TO BE CUT DRY. MACHINED SURFACES TO BE RMS 50 OR BETTER. NO EDGE DAMAGE OR FIBER SEPARATION SHOULD BE VISIBLE UNDER 10X MAGNIFICATION.

⑤ MEASURE SPECIMEN WIDTH 4 PLACES. WIDTH MUST NOT VARY BY MORE THAN 0.102-MM (0.004-IN.)

④ SPECIMEN WIDTH TO BE 22.225±0.127-MM (0.875±0.005-IN.)

③ MISMATCH OF TABS FROM SIDE TO SIDE NOT TO EXCEED 0.25-MM (0.01-IN.)

② TABS TO BE CUT FROM AN 8 PLY LAMINATE FABRICATED FROM PREPREG OF 1581 GLASS FABRIC IN A 350°F CURING EPOXY.

① SPECIMEN THICKNESS TO BE WITHIN ±0.08-MM (±0.003-IN.) OF THE AVERAGE OF 8 THICKNESS MEASUREMENTS.

Figure 6A.   Notched Composite Specimen

A-10
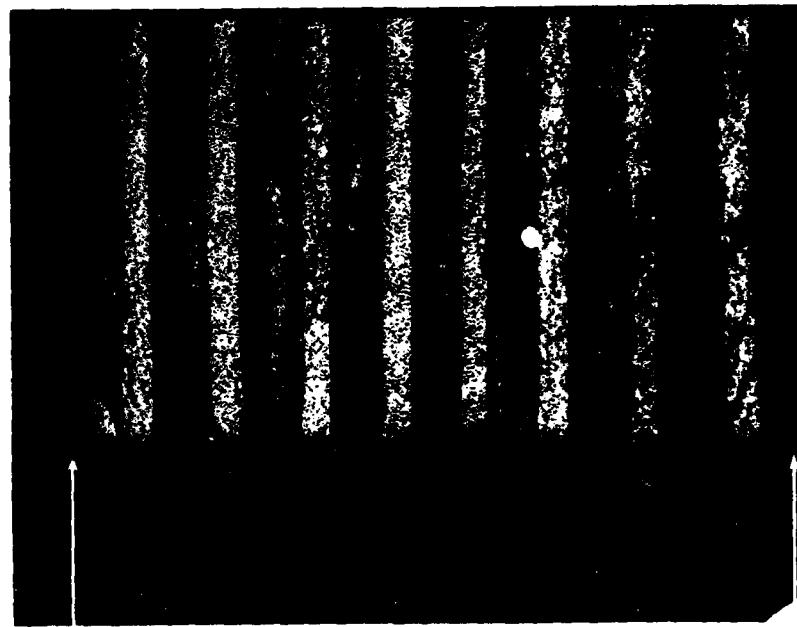
~ .125 in.

Drilling Direction ⟶

(a) Typical Clean Hole Containing Subsurface Cracking, Non-Diamond Drill
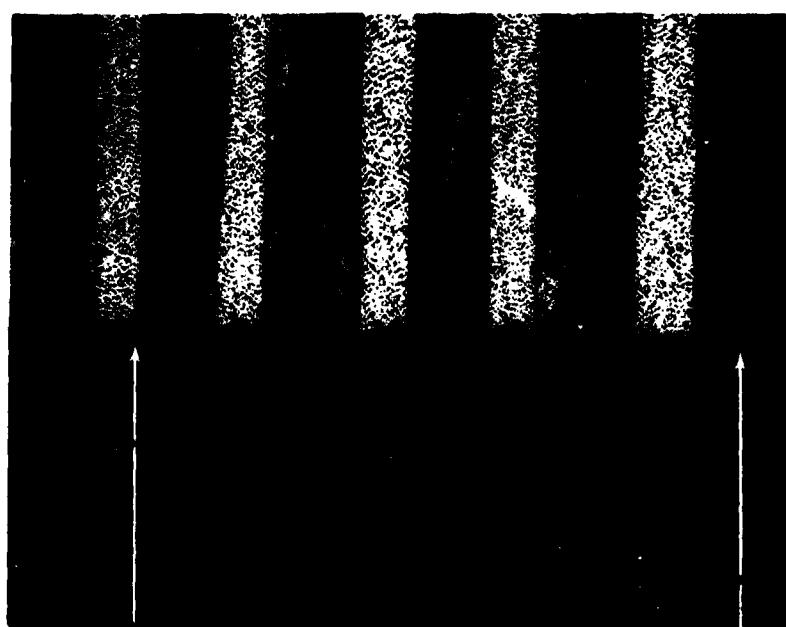
~ .062 in.

Drilling Direction ⟶

(b) Typical Clean Hole with no Subsurface Cracking, Diamond Drill

Figure 7A.   Effect of Drilling on Subsurface Cracking
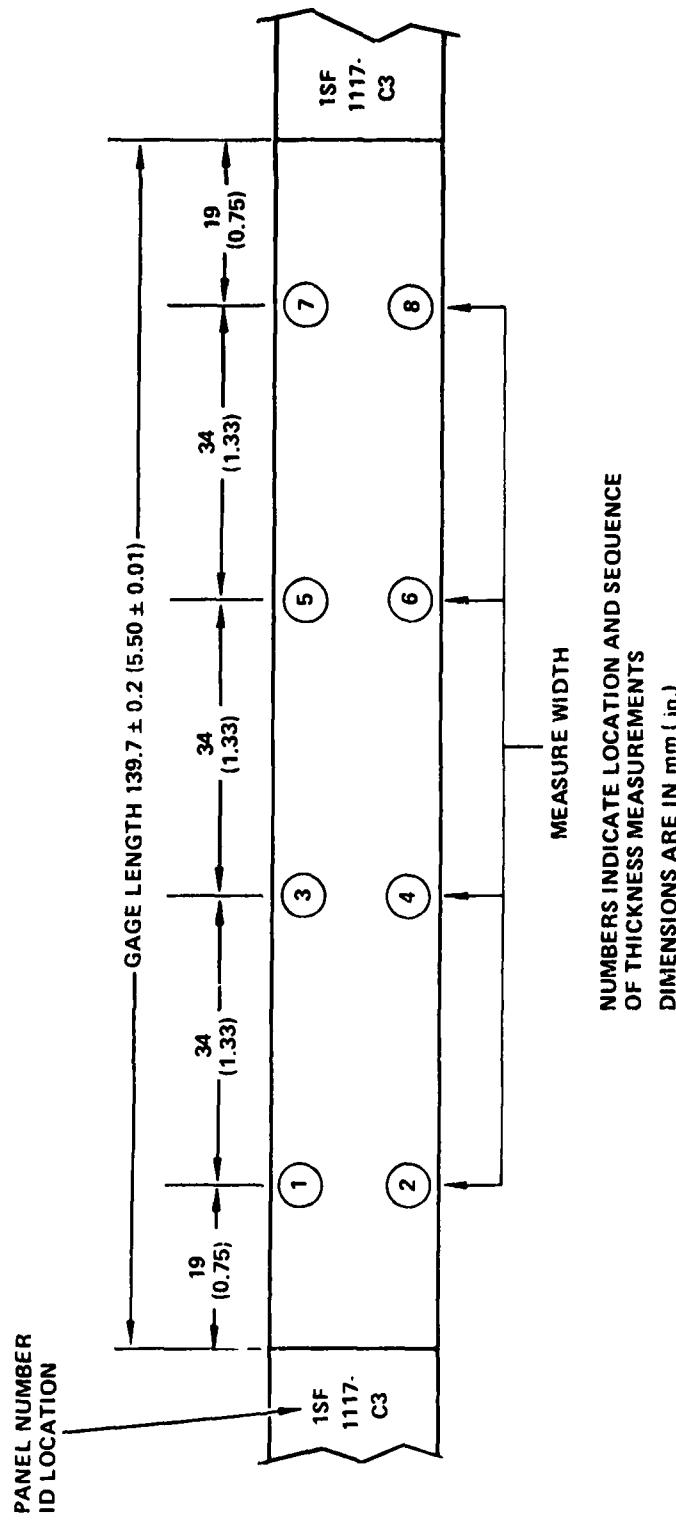
Figure 8A. Location of Thickness and Width Measurements

APPENDIX B

Static Data

TABLE B1

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS TESTED IN
ROOM TEMPERATURE, LABORATORY AIR (Sample Size = 55)

Sample ID	Avg. Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2 in.	Slope Deviation Load, P_y, lbs	Slope Deviation Stress, σ_y, ksi	Slope Deviation Strain, ϵ_y, in./in. in 2 in.	Initial Apparent Modulus of Elasticity, E_{ia}, psi x 10^6	Final Apparent Modulus of Elasticity, E_{ib}, psi x 10^6	Failure Location[a]
1SF1117-A13	.0754	6320	83.8	.014	3300	43.8	.0058	7.55	6.98	E
-B32	.0742	5920	79.8	.0108	3650	45.5	.0063	7.23	6.91	1/2 E
-C5	.0738	6500	88.1	.0119	4100	55.6	.0072	7.72	7.11	C
-C12[b]	.0744	5700	76.6	.0112	3650	49.1	.0069	7.11	6.18	1/2 E
-D24	.0729	5260	72.2	.0111	3600	49.4	.0072	6.86	5.83	C
2SF1117-A10	.0748	6020	80.5	.0112	3830	51.2	.0068	7.53	6.42	C
-A14	.0772	6340	82.1	.016	3620	49.5	.0068	7.28	6.15	C
-B23	.0758	6160	81.3	.0119	3900	51.4	.0071	7.25	6.23	1E
-C13	.0767	6240	81.4	.0114	3920	51.1	.0068	7.52	6.45	1/2 E
-22B	.0769	6440	83.7	.0115	4150	54.0	.0071	7.60	6.50	1E
1SF1121-A23	.0742	6260	84.4	.0117	4020	54.2	.0070	7.74	6.64	C
-B26	.0749	6170	82.4	.0113	4150	55.4	.0072	7.70	6.34	1E
-B29	.0747	6220	83.3	.0112	4200	56.2	.0072	7.81	6.69	C
-D10	.0739	6000	81.2	.0109	3920	53.0	.0067	7.92	7.10	C
-D24[b]	.0729	5600	76.8	.0110	3870	53.1	.0072	7.37	6.17	1E
2SF1121-A2	.0755	6280	83.2	.0119	4170	55.2	.0068	8.12	6.79	1/2 E
-22C	.0727	6340	87.2	.0118	4420	60.8	.0077	7.90	6.88	1/4 E
-C28	.0751	6120	81.5	.0112	4110	54.7	.0072	7.60	6.49	C
-D6	.0729	5900	80.9	.0110	4180	57.3	.0075	7.64	6.52	C
-D13[b]	.0745	5920	79.5	.0109	3940	52.9	.0070	7.56	6.54	1/2 E
1SF1122-A25[b]	.0706	5520	78.2	.0110	3850	54.5	.0073	7.47	6.20	1E
-B22	.0742	6680	90.0	.0120	4000	53.9	.0068	7.93	6.74	C
-C20	.0753	6480	86.0	.0118	4130	54.8	.0071	7.72	6.47	E
-D27	.0732	5960	81.4	.0114	3920	53.6	.0069	7.76	7.00	1/2 E
-D28	.0732	5760	78.7	.0106	4200	57.4	.0073	7.86	6.66	C
2SF1122-A6	.0733	6160	84.0	.016	4150	56.6	.0074	7.65	6.38	1/2 E
-A16	.0736	6500	88.3	.0129	4320	58.7	.0074	7.93	6.45	C
-B30	.0731	6380	87.3	.0119	4120	56.4	.0074	7.62	6.58	C
-C23	.0725	6380	88.0	.0120	4150	57.2	.0072	7.95	6.55	C
-D10	.0726	6520	89.8	.0118	4350	59.9	.0074	8.10	7.06	C

a - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
    E - Coupon end at or near tab, i.e., 1/2 E indicates failure $\sim$ 1/2 in. from tab

b - Coupon not included in Table B3

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS TESTED IN

ROOM TEMPERATURE, LABORATORY AIR (Sample Size = 55)

Sample ID	Avg. Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. 2 in.	Slope Deviation Load, P_y, lbs	Slope Deviation Stress, σ_y, ksi	Slope Deviation Strain, ε_y, in./in. 2 in.	Initial Apparent Modulus of Elasticity, E_{1a}, psi x 10^6	Final Apparent Modulus of Elasticity, E_{1b}, psi x 10^6	Failure Location[a]
1SF1130-A15	.0742	6400	86.2	.0117	4320	58.2	.0073	7.98	6.40	1E
-B18	.0731	6040	82.6	.0113	3700	50.6	.0065	7.79	6.67	C
-B28	.0753	6340	84.2	.0114	4090	54.3	.0069	7.87	6.47	E
-C2	.0745	6500	87.2	.0122	4270	57.3	.0074	7.75	6.54	C
-D7	.0740	5940	80.3	.0109	4070	55.0	.0070	7.86	6.59	1/2 E
2SF1130-A11	.0717	5820	81.2	.0110	3960	55.2	.0071	7.78	6.54	C
-A28b	.0716	5920	82.7	.0116	3800	53.1	.0067	7.92	6.63	C
-B12	.0721	5340	72.2	.0111	3850	53.4	.0075	7.12	5.72	C
-C6	.0740	5980	80.8	.0108	3900	52.7	.0065	8.11	6.59	C
-D7	.0724	6000	82.9	.0111	4030	55.7	.0071	7.84	6.65	1/2 E
1SF1132-A16b	.0743	5980	80.5	.0107	3780	50.9	.0063	8.08	6.56	1/2 E
-B11	.0722	5440	75.3	.0104	3780	52.4	.0066	7.93	6.75	1/2 E
-C27	.0744	6280	84.4	.0111	4170	56.0	.0070	8.01	6.89	1/2 E
-D3	.0734	6000	81.7	.0107	4040	55.0	.0067	8.22	6.73	1/2 E
-D28	.0729	6600	90.5	.0119	4330	59.4	.0075	7.92	6.69	C
2SF1132-A20	.0732	6060	82.8	.0108	3700	50.5	.0063	8.02	6.83	1E
-B23	.0738	5940	80.5	.0112	4300	58.3	.0076	7.67	6.27	1E
-C13b	.0732	5540	75.7	.0105	4140	56.6	.0075	7.54	6.40	C
-D16b	.0744	6100	82.0	.0103	4130	55.5	.0073	7.60	6.38	1E
-D25b	.0734	5540	75.5	.0110	4260	58.0	.0072	8.06	6.47	1E
1SF1133-A5	.0740	5920	80.0	.0107	4300	58.1	.0074	7.85	6.59	1/2 E
-A6	.0739	5920	80.1	.0109	4150	56.2	.0074	7.59	6.51	C
-B32	.0748	6400	85.6	.0114	4000	53.5	.0068	7.86	6.60	C
-C15	.0746	6220	83.4	.0108	4330	58.0	.0074	7.84	6.70	1/2 E
-D26	.0726	6280	86.5	.0116	4140	57.0	.0072	7.92	6.71	1/2 E

TABLE B2

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS TESTED IN ROOM TEMPERATURE LABORATORY AIR

(Sample Size = 25)

Sample ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress σ_{ult}, ksi	Ultimate Strain ϵ_{ult}, in./in. in 2.0 in.	Apparent Modulus of Elasticity, E, psi x 10^6	Failure Location a
2SF113?-A20	.1076	16410	152.5	.0104	14.7	C
-C8	.1072	17440	162.7	.0112	14.9	1E
-C13	.1061	15920	149.1	.0102	14.6	E
-D1	.1008	14420	143.1	.0096	14.9	E
-D12	.1009	15940	158.0	.0106	14.9	E
1SF113?-A20	.1096	18060	164.8	.0107	15.4	E
-B1	.1010	15920	157.6	.0202	15.4	C
-B25	.1096	18700	170.6	.0111	15.4	E
-C11	.1100	16680	151.6	.0100	15.2	E
-?3	.1150	19220	167.1	.0105	15.9	E
2SF113?-A2	.1102	17220	156.3	.0112	15.4	1E
-A19	.1194	18600	170.0	.0111	15.3	C
-B14	.1120	17840	159.3	.0105	15.2	1/2 E
-C24	.1084	16100	148.5	.0101	14.7	E
-D24	.1062	16440	154.8	.0102	15.2	E
1SF114G-A29	.1076	17580	163.4	.0106	15.4	C
-B32	.1091	17560	161.0	.0104	15.5	E
-C2	.1095	18540	169.3	.0106	16.0	E
-C16	.1089	17680	162.4	.0102	15.9	E
-D15	.1110	18200	164.0	.0105	15.6	1/2 E
2SF114G-A13	.1081	18880	174.6	.0111	15.7	E
-B21	.1091	19040	174.5	.0114	15.7	E
-B26	.1107	19080	172.4	.0110	15.7	1E
-C?6	.1112	17400	156.5	.0100	15.6	1E
-D17	.1095	17360	158.5	.0103	15.4	1/2 E

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
E = Coupon End at or near tab, i.e., 1/2 E indicates failure ~1/2 in. from tab

B4

TABLE B3

SUMMARY OF PANEL TO PANEL VARIATION OF LAMINATE 1 UN-NOTCHED STATIC TENSILE DATA TESTED IN ROOM TEMPERATURE, LABORATORY AIR

(Coupons marked in Table B1 by "h" are not included in Panel Averages)

Panel ID	1SF1117	2SF1117	1SF1121	2SF1121	1SF1122	2SF1122	1SF1130	2SF1130	1SF1132	2SF1132	1SF1133	Average all Panels	Average of Data Points
Average Area, in.^{2}	.0741	.0761	.0741	.0743	.0733	.0730	.0742	.0724	.0734	.0736	.0740	.0739	
Std. Deviation	.00106	.00106	.00128	.0011	.0017	.00046	.0080	.00097	.00093	.00051	.00096	.00092	
Coeff. of Var. %	1.4	1.4	1.7	1.4	2.4	0.64	1.1	1.3	1.3	0.69	1.2	1.28	
Average Ultimate Stress, ksi	83.9	81.8	83.2	81.3	84.0	87.5	84.1	81.9	84.3	81.8	83.1	83.3	82.3
Std. Deviation	4.2	1.20	2.84	1.53	4.99	2.15	2.77	1.06	4.46	1.17	3.02	1.75	4.13
Coeff. of Var. %	4.9	1.5	3.4	1.9	5.9	2.5	3.3	1.3	5.3	1.4	3.5	2.1	5.0
Average Ultimate Strain, in./in., in 2 in.	.0114	.0115	.0115	.0112	.0114	.0118	.0115	.0111	.0111	.0108	.0112	.0113	
Std. Deviation													.0006
Coeff. of Var. %	4.8	2.2	3.8	4.0	5.4	1.3	4.2	10	5.1	4.2	3.6		5.0
Average Slope Deviation Stress, σ, ksi	48.3	51.4	57.0	55.0	54.9	57.8	55.1	54.2	55.3	54.8	46.6		
Std. Deviation	6.38	1.62	2.77	1.81	1.73	1.50	2.97	1.50	3.50	3.75	1.88		
Coeff. of Var. %	13.2	3.1	4.9	3.3	3.1	2.6	5.4	2.8	6.3	7.2	3.3		
Average Slope Deviation Strain, in./in., in 2 in.	.0064	.0069	.0073	.0071	.0070	.0074	.0070	.0068	.0069	.0071	.0072		
Std. Deviation	11.0	2.4	5.4	4.2	3.2	1.2	5.1	4.4	7.4	9.6	3.6		
Coeff. of Var. %													
Average Initial Apparent Modulus of Elasticity, E_{ia}, psi x 10^6	7.50	7.44	7.82	7.73	7.82	7.85	7.85	7.91	8.06	7.76	7.81		7.73
Std. Deviation	0.25	0.16	0.24	0.26	0.095	0.21	0.09	0.14	0.13	0.22	0.13		0.281
Coeff. of Var. %	3.3	2.1	3.1	3.4	1.2	2.6	1.1	1.8	1.6	2.9	1.6		3.64
Average Final Apparent Modulus of Elasticity, E_{fa}, psi x 10^5	7.00	6.35	6.67	6.48	6.72	6.60	6.53	6.60	6.72	6.49	6.62		6.57
Std. Deviation	0.10	0.15	0.19	0.14	0.22	0.27	0.10	0.048	0.14	0.30	0.083		0.282
Coeff. of Var. %	1.5	2.4	2.9	2.1	3.3	4.0	1.6	0.74	2.0	4.6	1.3		4.3

TABLE B4

SUMMARY OF PANEL TO PANEL VARIATIONS OF LAMINATE 2 UN-NOTCHED STATIC TENSILE DATA TESTED IN ROOM TEMPERATURE, LABORATORY AIR

Panel ID	2SF1133	1SF1137	2SF1137	1SF1149	2SF1149	Average of all Panels	Average of all Points
Average Area, in.^{2}	.1045	.1090	.1112	.1092	.1097		.1087
Std. Deviation	.0034	.0050	.0050	.0012	.0012		.0040
Coeff. of Var. %	3.2	4.6	4.5	1.1	1.1		3.7%
Average Ultimate Stress, σ_{ult}, ksi	153.1	162.3	157.8	164.0	167.3	160.9	161.0
Std. Deviation	7.62	7.66	7.89	3.16	9.02	5.54	8.42
Coeff. of Var. %	5.0	4.7	5.0	1.9	5.4	3.4	5.23
Average Ultimate Strain, ε_{ult}, in./in. in 2 in.	.0104	.0105	.0106	.0105	.0108		.0105
Std. Deviation	.00058	.00038	.00051	.00017	.00058		.00046
Coeff. of Var. %	5.6	3.6	3.5	1.6	5.4		4.4
Average Apparent Modulus of Elasticity, E_2, psi x 10^6	14.8	15.5	15.3	15.7	15.6		15.3
Std. Deviation	0.14	0.26	0.10	0.26	0.13		0.38
Coeff. of Var. %	0.96	1.7	0.65	1.6	0.83		2.5

TABLE B5

RANK ORDER OF UN-NOTCHED LAMINATE 1, ROOM TEMPERATURE STATIC
TENSION DATA SHOWING EFFECT OF LINE DISCONTINUITY

Rank Order Index	Ultimate Tensile Strength, ksi	Rank Order Index	Ultimate Tensile Strength, ksi
1	66.8**	37	82.0
2	66.8**	38	82.1
3	72.2*	39	82.1
4	72.2*	40	82.4
5	73.7*	41	82.6
6	73.9**	42	82.7
7	75.3*	43	82.8
8	75.5*	44	82.9
9	75.7*	45	83.2
10	76.6*	46	83.3
11	76.8*	47	83.4
12	77.3*	48	83.7
13	77.7	49	83.8
14	78.2*	50	84.0
15	78.7*	51	84.0
16	78.9	52	84.2
17	79.0	53	84.4
18	79.5*	54	84.4
19	79.8*	55	85.5
20	79.8	56	85.7
21	80.0	57	86.0
22	80.1	58	86.0
23	80.3	59	86.2
24	80.5	60	86.2
25	80.5	61	86.5
26	80.5	62	87.2
27	80.8	63	87.2
28	80.9	64	87.2
29	81.2	65	87.3
30	81.2	66	88.0
31	81.3	67	88.1
32	81.3	68	88.3
33	81.4	69	89.3
34	81.4	70	90.0
35	81.5	71	90.4
36	81.7	72	90.5

*   Coupon Contained 0° Line Discontinuity

**   Coupon Contained 90° Line Discontinuity

TABLE B6

RANK ORDER OF UN-NOTCHED LAMINATE 2, ROOM TEMPERATURE
STATIC TENSION DATA SHOWING EFFECT OF LINE DISCONTINUITY

Rank Order Index	Ultimate Tensile Strength, ksi
1	143.1
2	148.5*
3	149.1*
4	151.6*
5	152.5
6	154.3*
7	156.3
8	156.5
9	157.6
10	158.0*
11	158.5
12	159.3
13	161.0
14	162.4
15	162.7
16	163.4
17	164.0
18	164.3
19	167.1
20	169.3
21	170.0
22	170.6
23	172.4
24	174.5
25	174.6

* - Coupon contained 0° line discontinuity.

TABLE B7

TENSION TESTED RESULTS OF NOTCHED LAMINATE 1 COUPONS TESTED IN ROOM TEMPERATURE, LABORATORY AIR

(Sample Size = 20)

2R = 0.250 in.

Sample ID	Average Area, in.^{2}	Ultimate Load P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi
1SF1117-26A	.0740	2865	38.7
-17B	.0760	3220	42.4
2SF1117- 9A	.0747	3145	42.1
-15D	.0741	2810	37.9
1SF1121-30A	.0732	3145	42.1
- 8C	.0741	2965	40.5
2SF1121-19A	.0748	3070	41.0
- 7D	.0729	3155	43.3
1SF1122-12B	.0746	2840	38.1
-17D	.0741	3135	42.3
2SF1122-8C	.0733	3090	42.2
1SF1130- 3A	.0739	3030	41.0
- 8B	.0767	3235	42.2
2SF1130-10A	.0713	2920	41.0
1SF1132-31A	.0732	2970	40.6
-14C	.0737	2985	40.5
2SF1132-20B	.0732	3095	42.3
- 4C	.0725	3170	43.7
1SF1133-4D	.0734	3070	41.8
-6D	.0736	2910	39.5
Average	.0739		41.2
Std. Dev.	.00117		1.62
Coeff. of Var.	1.6%		3.9%

TABLE B8

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS TESTED AT 82.2°C (180°F)
COUPONS CONDITIONED AT 82.2°C (180°F) AT 90% R.H.

Sample ID	Avg. Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. 2 in.	Slope Deviation Load, P_y, lbs	Slope Deviation Stress, σ_y, ksi	Slope Deviation Strain, ε_y, in./in. 2 in.	Initial Apparent Modulus of Elasticity, E_{ia}, psi x 10^6	Final Apparent Modulus of Elasticity, E_{ib}, psi x 10^6	Failure Location d
1SF1117-B1	.0727	5650	77.7	.0113	3850	53.0	.0074	7.16	6.35	c
2SF1117-A19	.0760	5820	76.6	.0102	- a	- a	- a	7.31	7.24	c
1SF1121-A11	.0728	5930	81.4	.0111	- a	- a	- a	7.34	7.34	c
D9	.0739	6220	84.2	.0113	3750	50.7	.0066	7.69	7.13	1E
1SF1122-A6	.0735	5860	79.7	.0105	- b	- b	- b	7.48	7.48	1E
D31	.0725	5900	81.4	.016	- b	- b	- b	7.24	7.24	1E
2SF1121-B15	.0754	4950	65.6	.0090	.3250	42.6	.0057	7.34	7.34	c
B23	.0762	5900	77.4	.0106	- b	- b	- b	7.48	7.09	c
2SF1122-B20	.0755	6630	87.8	.0111	- b	- b	- b	7.52	7.52c	c
D28	.0729	6270	86.0	.0112	- b	- b	- b	7.72	7.72	c
1SF1130-A10	.0732	6310	86.2	.0113	- b	- b	- b	7.63	7.63	c
C30	.0754	5750	76.2	.0107	- b	- b	- b	7.13	7.13	1E
2SF1130-A20	.0732	6030	82.4	.0107	- b	- b	- b	7.52	7.52c	c
D22	.0753	6550	87.0	.0114	- b	- b	- b	7.73	7.73c	c
1SF1132-A25	.0724	5680	78.4	.0124	- b	- b	- b	7.14	7.14	c
1SF1132-D22	.0754	5610	78.6	.0096	- b	- b	- b	7.63	7.63	1/2 E
2SF1132-B31	.0747	5920	79.2	.0103	- b	- b	- b	7.58	7.58	1/2 E
C30	.0742	6080	81.9	.0119	- b	- b	- b	7.01	7.01	c
1SF1133-B29	.0755	6000	79.5	.0106	- b	- b	- b	7.37	7.37	c
C21	.0760	6380	83.9	.0109	- b	- b	- b	7.70	7.70c	E
Avg.	.0743		80.6	.0109				7.44		
Std. Dev.	.00134		5.00	.00077				0.22		
Coeff. of Var. %	1.80		6.21	7.06				2.98		

a - Test Record Damaged

b - No values obtained since a and b slopes are the same

c - Slight curvature just prior to failure

d - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
E - Coupon end at or near tab, i.e., 1/2 E indicates failure ~ 1/2 in. from tab.

TABLE B9

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS TESTED AT 82.2°C (180°F),

COUPONS CONDITIONED AT 82.2°C (180°F) AT 90% R.H.

Sample ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain ϵ_{ult}, in./in. in 2.0 in.	Apparent Modulus of Elasticity, E_2, psi x 10^6	Failure Location a
2SF1133-A6	.100	15050	150.5	.0111	13.6	E
A18	.1039	15600	150.1	.0108	13.9	E
A22	.1087	17600	161.9	.0112	14.5	E
C5	.1040	16300	156.7	.0111	14.1	C
1SF1137-A9	.1101	19750	179.4	.0121	14.8	1/2 E
A18	.1079	17200	159.4	.0112	14.2	C
B17	.1117	19125	171.2	.0116	14.8	C
C9	.1140	19250	168.9	.0114	14.8	C
2SF1137-A12	.1066	16875	158.3	.0110	14.4	1/2 E
A25	.1079	18500	171.4	.0114	15.0	E
B9	.1135	19125	168.5	.0112	15.0	E
B12	.1095	18700	170.8	.0118	14.5	E
1SF1149-A5	.1105	19260	174.3	.0116	15.0	E
A26	.1071	19080	178.2	.0115	15.5	E
C32	.1096	18000	164.2	.0119	13.8	E
D31	.1082	16800	155.3	.0102	15.2	E
2SF1149-A9	.1085	18620	171.6	.0112	15.3	C
A20	.1107	16300	147.2	.0092	16.0	C
A25	.1074	18040	168.0	.0111	15.1	E
B27	.1123	18800	167.4	.0109	15.4	1E
Avg.	.1086	17899	164.7	.0112	14.7	
Std. Dev.	.0034	1361	9.36	.000626	0.619	
Coeff. of Var.%	3.09	7.61	5.68	5.61	4.2	

a - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
    E - Coupon end at or near tab, i.e., 1/2 E indicates failure ~ 1/2 in. from tab

TABLE B10

TENSION TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS TESTED AT
82.2°C (180°F), 90% R.H., Laboratory Air
2R = 6.35 mm (0.250 in.)

Coupon ID	Average Area,		Ultimate Load P_{ult}		Ultimate Stress, σ_{ult},	
	mm^2	(in.^{2})	kN	(lbs)	MPa	(ksi)
1SF1117-A20	49.9	(.0773)	13.43	(3020)	270	(39.1)
-A30	48.8	(.0757)	13.26	(2980)	272	(39.4)
2SF1117-C31	49.9	(.0774)	13.12	(2950)	214	(31.1)
1SF1121-B28	49.1	(.0761)	13.70	(3080)	279	(40.5)
-C9	49.1	(.0761)	12.99	(2920)	265	(38.4)
2SF1121-A22	49.5	(.0767)	14.68	(3300)	296	(43.0)
-D4	48.6	(.0753)	13.92	(3130)	287	(41.6)
1SF1122-A14	47.8	(.0741)	13.74	(3090)	288	(41.7)
-C22	48.9	(.0758)	13.21	(2970)	215	(31.2)
2SF1122-B17	48.1	(.0745)	12.94	(2910)	270	(39.1)
-D22	48.6	(.0753)	14.37	(3230)	296	(42.9)
1SF1130-B1	47.6	(.0738)	12.54	(2820)	248	(36.0)
-C26	49.1	(.0761)	13.39	(3010)	273	(39.6)
2SF1130-B21	47.9	(.0742)	12.99	(2920)	272	(39.4)
1SF1132-A1	47.4	(.0734)	14.01	(3150)	296	(42.9)
-C5	47.5	(.0737)	12.23	(2750)	257	(37.3)
2SF1132-B3	46.4	(.0720)	14.81	(3330)	318	(46.2)
1SF1133-B8	48.9	(.0758)	13.57	(3050)	277	(40.2)
-C1	44.6	(.0692)	10.90	(2450)	244	(35.4)
				Avg.		39.2
				Std. Dev.		3.83
				Coeff. of Var. %		9.77

TABLE B11

COMPRESSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS TESTED IN ROOM TEMPERATURE, LABORATORY AIR

(Sample Size = 20)

Sample ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure E_{sf}, psi x 10^6	Secant Modulus at 35 ksi E_{s35}, psi x 10^6	Failure Locations [a]
1SF111/-A6	.0750	5660	75.5	.0121	6.24	7.14	1E
-A28	.0745	5460	73.3	.0113	6.49	7.29	C
2SF111/-B25	.0771	6040	78.3	.0125	6.26	7.00	C
1SF121-C6	.0722	5780	80.0	.0130	6.15	7.14	C
-C14	.0751	6000	79.9	.0130	6.15	7.45	C
2SF121-C5	.0722	6100	84.5	.0137	6.17	7.45	C
-C24	.0720	6230	86.5	.0148	5.85	7.00	C
1SF122-C15	.0742	6600	88.9	.0152	5.85	7.78	1E
-D20	.0746	5780	77.5	.0129	6.01	7.29	1E
2SF122-B22	.0752	6800	90.4	.0150	6.03	7.78	C-1E
-C6	.0733	6520	88.9	.0146	6.09	7.61	C
1SF130-A9	.0730	5640	77.3	.0122	6.34	7.45	C
-B19	.0742	5540	74.7	.0120	6.22	7.29	C
2SF130-B31	.0736	6420	87.2	.0149	5.85	7.14	C
1SF132-A6	.0710	5440	76.6	.0117	6.55	7.29	C
-C18	.0748	6160	82.4	.0132	6.24	7.14	C
2SF132-C1	.0706	6380	90.4	.0151	5.99	7.29	C
-C17	.0725	5600	77.2	.0126	6.13	7.14	C
1SF133-C18	.0734	6720	91.6	.0162	5.65	7.14	C
-C19	.0742	6280	84.6	.0141	6.00	7.29	C
Average	.0737		82.3	.0135	6.11	7.30	
Std. Dev.	.0016		5.96	.0014	0.22	0.22	
Coeff. of Var.	2.2%		7.2%	10.3%	3.6%	3.1%	

a - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
E - Coupon end at or near tab, i.e., 1/2 E indicates failure ~ 1/2 inch from tab.

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TABLE B12

COMPRESSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS TESTED IN ROOM TEMPERATURE LABORATORY AIR

(Sample Size = 20)

Sample ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2.0 in.	Apparent Modulus of Elasticity, E_A, psi x 10^6	Secant Modulus at 70 ksi, E_{S70} psi x 10^6	Failure Location
2SF1133-A11	.1022	12900	126.2	.0107	11.8	13.0	C
-B12	.1037	13620	131.3	.0223	10.7	12.3	1E
-C11	.1075	15020	139.7	.0122	11.4	13.0	C
-D8	.1039	17140	165.0	.0151	10.9	13.0	C
1SF1137-A16	.1117	16380	146.6	.0138	10.6	13.2	C-1/2E
-A24	.1070	14900	139.2	.0114	12.2	13.5	1E
-A27	.1082	16820	155.4	.0138	11.3	13.5	C
-D15	.1127	16680	148.0	.0128	11.6	13.2	C
2SF1137-B7	.1113	17140	155.1	.0134	11.6	13.2	C
-B23	.1099	18500	168.3	.0164	10.3	13.2	C
-C20	.1105	15180	137.4	.0115	11.9	13.5	C
-C31	.1078	15500	143.8	.0121	11.9	13.2	E
1SF1149-A1	.1055	14980	142.0	.0128	11.1	13.0	1/2E
-A24	.1042	14940	143.4	.0123	11.7	13.2	C
-D8	.1076	16680	155.0	.0132^b	11.7^b	13.7	C
-D28	.1077	18100	168.0	-	-	13.7	C
2SF1149-C2	.1098	16220	147.7	.0140	10.6	13.7	C
-D2	.1120	17280	154.3	.0150	10.3	12.7	1/2E
-D25	.1056	14580	138.1	.0132	10.5	13.7	C
-D32	.1120	15740	140.5	.0144	9.8	13.2	C
Average	.1080		147.2	.0132	11.2	13.2	
Std. Dev.	.0032		11.5	.0014	.68	0.35	
Coeff. of Var.	2.9%		7.8%	10.8%	6.1%	2.7%	

a - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;

E - Coupon end at or near tab, i.e., 1/2E indicated failure ~ 1/2 in. from tab.

b - Extensometer Failure

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TABLE B13

STATIC COMPRESSION TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS TESTED IN ROOM TEMPERATURE, LABORATORY AIR

(Sample Size = 20)

Sample ID	Avg. Area, in.^{2}	Ultimate Load, P_{ult}, lbs.	Ultimate Stress σ_{ult}, ksi	Ultimate Strain ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Secant Modulus at 35 ksi, E_{S35}, psi x 10^6
1SF1117-5B	.0759	3620	45.8	.0078	5.87	6.36
-26B	.0760	2925	38.5	.0093	4.15	4.22
2SF1117-5A	.0754	3295	43.7	.0072	6.07	6.36
-29A	.0758	3830	50.5	.0086	5.87	6.86
1SF1121-31A	.0736	3395	46.1	.0075	6.15	6.86
-19C	.0745	3450	46.3	.0081	5.72	6.14
2SF1121-13A	.0734	3370	45.9	.0080	5.74	6.03
1SF1122-32B	.0730	3270	44.8	.0074	6.05	6.60
-18D	.0733	3395	46.3	.0079	5.86	5.83
2SF1122-20C	.0748	3750	50.1	.0102	4.91	5.22
-25C	.0721	3400	47.2	.0094	5.02	5.83
1SF1130-19C	.0732	2940	40.1	.0068	5.90	6.14
-27C	.0748	3455	46.2	.0077	6.00	6.36
2SF1130-21D	.0746	3595	48.2	.0081	5.95	6.36
1SF1132-8B	.0739	3675	49.7	.0084	5.92	6.36
-12B	.0723	3165	43.8	.0075	5.84	6.14
2SF1132-25A	.0715	2765	38.7	.0063	6.14	6.25
-28B	.0745	3100	41.6	.0066	6.30	6.36
1SF1133-10B	.0750	3130	41.7	.0067	6.22	6.48
-15B	.0755	3690	48.9	.0082	5.96	6.25
Average	.0742		45.2	.0079	5.78	6.15
Std. Dev.	.0013		3.60	.00098	0.52	0.58
Coeff. of Var.	1.8%		8.0%	12.5%	9.0%	9.4%
Unnotched Properties			82.3			

TABLE B14

COMPRESSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS TESTED AT 82.2°C (180°F), COUPONS CONDITIONED AT 82.2°C

(180°F) at 90% R.H.

(Sample Size = 20)

Sample ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure E_{sr}, psi x 10^6	Secant Modulus at 35 ksi, E_{35}, psi x 10^6	Failure Locations[a]
1SF1117-C24	.0716	5320	74.2	.0101	7.34	7.14	C
-C31	.0761	5280	69.4	.0139	4.99	7.77	E
2SF1117-A6	.0755	4780	63.3	.0104	6.08	7.29	C
1SF1121-D12	.0702	4920	70.1	.0117	5.99	7.29	C
2SF1121-B19	.0750	5380	71.7	.0104	6.89	7.60	E
-B29	.0744	5020	67.5	.0133	5.07	7.60	C
1SF1122-B30	.0727	5840	80.3	.0121	6.69	7.44	C
-D32	.0730	5520	75.7	.0158	4.79	7.29	1/2 E
2SF1122-B28	.0741	5845	78.9	.0136	5.80	7.60	C
-D18	.0739	5120	69.3	.0103	6.72	7.44	1/2 E
1SF1130-A29	.0731	4460	63.7	.0097	6.56	7.44	C
-B24	.0749	3980	53.1	.0085	6.24	7.14	C
2SF1130-B29	.0736	4830	65.6	.0098	6.69	7.95	C
-D28	.0728	5230	71.8	.0104	6.90	7.29	1/2 E
1SF1132-A3	.0731	4925	67.3	.0103	6.53	7.60	C
-C30	.0728	5360	73.6	.0122	6.03	7.95	C
2SF1132-A9	.0731	5420	74.1	.0114	6.50	7.67	C
-C7	.0752	4890	65.0	.0097	6.70	7.82	1/2 E
1SF1133-B27	.0751	5650	75.2	.0118	6.36	7.14	C
-D21	.0746	5380	72.1	.0123	5.81	6.82	C
Average	.0737		70.1	.0114	6.23	7.46	
Std. Dev.	.0014		6.20	.00178	.678	0.296	
Coeff. of Var. %	1.93		8.85	15.6	10.9	3.96	

a - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
    E - Coupon end at or near tab, i.e., 1/2 E indicates failure ~1/2 in. from tab

TABLE B15

COMPRESSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS TESTED AT 82.2°C (180°F)

COUPONS CONDITIONED AT 82.2°C (180°F) at 90% R.H.

(Sample Size = 20)

Sample ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2.0 in.	Apparent Modulus of Elasticity E_A, psi x 10^7	Secant Modulus at 70 ksi, E_{S70}, psi x 10^6	Failure Location[a]
2SF1133-A1	.1026	14060	137.0	.0122	11.2	13.7	E
-A30	.1032	12500	121.1	.0117	10.4	12.7	C
-B21	.1069	13460	125.9	.0106	11.9	13.2	E
-C21	.1078	11920	110.6	.0089	12.4	13.2	E
1SF1137-A4	.1121	13960	124.5	.0092	13.5	13.7	E
-B8	.1119	12920	115.5	.0095	12.2	13.5	E
-B26	.1125	15420	137.0	.0118	11.6	13.2	E
-C30	.1098	13720	124.9	.0101	12.4	13.5	C
2SF1137-A17	.1097	14120	128.7	.0106	12.1	13.5	C
-A26	.1090	13460	123.5	.0108	11.4	14.0	C
-D6	.1060	9580	90.4	.0069	13.1	13.2	E
-D31	.1061	9540	89.9	.0067	13.4	13.7	1/2 E
1SF1149-A2	.1127	13280	117.8	.0089	13.2	14.0	E
-C1	.1033	11960	115.7	.0094	12.3	13.5	C
-C4	.1106	12440	112.5	.0087	12.9	14.0	C
-D21	.1116	13420	120.2	.0099	12.1	13.7	E
2SF1149-A2	.1119	13780	123.1	.0122	10.1	13.5	E
-B9	.1123	12700	113.1	.0089	12.7	14.3	E
-B23	.1092	12580	115.2	.0094	12.3	13.7	E
-C21	.1110	13120	118.1	.0104	11.4	14.9	E
Average	.1090		118.2	.0098	12.1	13.6	
Std. Dev.	.0033		12.0	.0015	0.92	0.469	
Coeff of Var. %	3.04		10.2	15.5	7.58	3.44	

a - C - Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
E - Coupon end at or near tab, i.e., 1/2 E indicates failure ~ 1/2 in. from tab

TABLE B16

COMPRESSION TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS TESTED AT

62.2°C (180°F), 90% R.H., Laboratory Air

2R = 6.35 mm (0.250 in.)

Coupon	Average Area,		Ultimate Load P_{ult}		Ultimate Stress, σ_{max},	
ID	mm^2	$(in.^2)$	kN	(lbs)	MPa	(ksi)
1SF1117-B19	49.8	(.0772)	13.61	(3060)	273	(39.6)
-C22	48.6	(.0754)	13.06	(2935)	268	(38.9)
2SF1117-B28	50.4	(.0782)	13.77	(3095)	273	(39.6)
-C11	50.1	(.0776)	13.88	(3120)	277	(40.2)
1SF1121-A7	47.6	(.0738)	13.32	(2995)	280	(40.6)
-D18	48.3	(.0749)	13.34	(3000)	276	(40.1)
2SF1121-A9	48.6	(.0754)	14.41	(3240)	296	(43.0)
-D15	48.6	(.0754)	13.70	(3080)	281	(40.8)
1SF1122-A3	47.5	(.0737)	12.39	(2785)	261	(37.8)
-D14	48.1	(.0746)	14.50	(3260)	301	(43.7)
2SF1122-A5	47.9	(.0743)	13.52	(3040)	282	(40.9)
-D29	46.2	(.0716)	13.68	(3075)	296	(42.9)
1SF1130-B10	48.5	(.0752)	13.43	(3020)	277	(40.2)
-D27	48.4	(.0750)	11.23	(2525)	232	(33.7)
2SF1130-A14	47.8	(.0741)	13.08	(2940)	274	(39.7)
-C23	48.6	(.0754)	12.90	(2900)	265	(38.5)
1SF1132-C11	47.3	(.0733)	12.48	(2805)	264	(38.3)
2SF1132-A10	47.4	(.0735)	13.70	(3080)	289	(41.9)
-D31	48.4	(.0751)	12.37	(2780)	255	(37.0)
1SF1133-A7	48.2	(.0747)	13.95	(3135)	290	(42.0)
				Avg.		40.0
				Std. Dev.		2.30
				Coeff. of Var. %		5.76

TABLE B17

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS (SAMPLE SIZE = 25)

Strain Rate ≈ 0.015 in./in./min, Tested April 1975

Sample ID	Min. Area, in.^{2}	Ultimate Load, P_{ult},lbs	Ultimate Stress, σ_{ult},ksi	Ultimate Strain ϵ_{ult},in./in. in 2 in.	Slope Deviation Load, F_y,lbs	Slope Deviation Stress, σ_y,ksi	Slope Deviation Strain, ϵ_y,in./in. in 2 in.	Initial Apparent Modulus of Elasticity, E_{ia}, psi x 10^6	Final Apparent Modulus of Elasticity, E_{ib}, psi x 10^6
578-23B	.0835	6100	73.0	.0099	4000	47.9	.0062	7.73	6.65
2A	.0837	5800	69.3	.0102	4150	49.6	.0069	7.18	5.97
15A	.0857	5940	69.3	.0107	3750	43.8	.0063	6.95	5.98
580-19B	.0833	5930	71.8	.0097	3780	45.4	.0056	8.10	7.06
18A	.0820	6080	74.2	.0090	3690	45.0	.0055	8.18	7.17
3A	.0827	6240	75.4	.0103	3960	47.9	.0059	8.12	6.72
582-15A	.0840	5680	67.6	.0090	4090	48.7	.0062	7.85	6.61
8B	.0831	5350	64.4	.0038	3640	43.8	.0056	7.82	6.69
20B	.0815	5380	66.0	.0088	3800	46.6	.0059	7.90	6.82
583-24B	.0305	5800	72.0	.0103	3390	42.1	.0054	7.80	6.54
25B	.0821	5960	72.6	.0101	3570	43.5	.0056	7.76	6.41
8A	.0836	5900	70.6	.0099	3950	47.2	.0063	7.50	5.98
594-11A	.0322	5100	62.0	.0086	4100	49.9	.0066	7.56	5.79
10B	.0819	5850	71.4	.0088	4170	50.2	.0064	7.96	6.10
596-4A	.0820	5790	70.6	.0095	3780	46.1	.0061	7.56	6.78
12B	.0827	5730	69.9	.0100	3650	44.1	.0058	7.61	5.90
601-11B	.0820	5300	64.6	.0093	3800	46.3	.0064	7.24	6.10
6B	.0815	5700	69.9	.0093	4250	52.2	.0066	7.90	6.46
603-25A	.0819	5340	65.2	.0091	3620	44.2	.0058	7.62	6.43
6A	.0821	5740	69.9	.0098	4200	51.2	.0069	7.41	6.77
604-8B	.0835	5820	69.7	.0099	3150	37.7	.0051	7.40	6.65
22A	.0824	5600	68.0	.0100	3100	37.6	.0051	7.38	6.74
24A	.0817	5280	64.6	.0090	2830	34.6	.0047	7.37	6.80
606-24B	.0804	5300	66.0	.0090	3340	41.5	.0055	7.55	6.56
14A	.0841	6000	71.3	.0101	3800	45.2	.0061	7.41	6.26
Average			69.2 +6.2 -7.2	.0096 +.0011 -.0010		45.3 + 6.9 -10.7	.0059 +.0010 -.0012	7.64 +0.54 -0.69	6.48 +0.70 -0.68

TABLE B18

TENSILE TEST RESULTS FOR PANEL INH 693, UN-NOTCHED LAMINATE 1 COUPONS (SAMPLE SIZE -5)

Strain Rate = 0.015 in./in./min, Tested March 1976

Sample ID	Min. Area in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2.0 in.	Slope Deviation Load, P_y, lbs	Slope Deviation Stress, σ_y, ksi	Slope Deviation Strain, ϵ_y, in./in. in 2.0 in.	Initial Appar. Modulus of Elasticity, E_{la}, psi x 10⁶	Final Appar. Modulus of Elasticity, E_{lb}, psi x 10⁶
593- 4A	.0852	6740	79.1	.0104	4300	50.5	.0062	7.82	6.18
-11B	.0853	5640	66.1	.0091	3800	45.1	.0056	7.82	6.51
-17B	.0876	5620	64.2	.0089	4500	51.4	.0068	7.61	6.34
- 8C	.0853	5920	69.4	.0090	4300	50.4	.0062	7.33	6.51
-19C	.0861	6100	70.8	.0101	3800	44.1	.0058	7.26	6.11
Average Panel 693			69.9	.0095		48.3	.0061	7.57	6.33
			+ 9.2	+.0009		+ 2.2	+.0007	+0.44	+0.18
			- 5.7	-.0006		- 3.1	-.0003	-0.31	-0.22
Average Panels 278 to 306			69.2	.0096		45.3	.0059	7.64	6.48
			+ 6.2	+.0011		+ 6.9	+.0010	+0.54	+0.70
			- 7.2	-.0010		-10.7	-.0012	-0.69	-0.68

TABLE B19

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS (SAMPLE SIZE = 10)

STRAIN RATE = 0.015 in./in./min, TESTED SEPTEMBER 1977

Sample ID	Average Area, in.^{2}	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2 in.	Slope Deviation Stress, σ_y, ksi	Slope Deviation Strain, ϵ_y, in./in. in 2 in.	Initial Apparent Modulus of Elasticity, E_{la}, psi x 10^6	Final Apparent Modulus of Elasticity, E_{lb}, psi x 10^6
INH 693- 6A	.0856	70.5	.0111	46.7	.0064	7.30	6.57
- 8A	.0864	79.4	.0111	66.0	.0090	7.33	5.79
-13A	.0871	74.4	.0109	55.1	.0077	7.16	6.17
-27A	.0861	75.3	.0108	56.9	.0079	7.20	6.10
- 6B	.0851	71.7	.0102	53.5	.0073	7.32	6.39
- 8B	.0865	76.5	.0104	56.1	.0075	7.48	6.55
-12B	.0873	66.3	.0093	49.8	.0069	7.22	6.51
- 2C	.0865	74.0	.0104	-	-	7.40	-
- 4C	.0868	75.6	.0113	53.0	.0078	6.79	6.53
-21C	.0874	71.3	.0102	53.2	.0074	7.19	6.58
Average		73.5	.0106	54.2	.0075	7.24	6.36

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TABLE 20

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS (SAMPLE SIZE = 10)
STRAIN RATE $\simeq$ 0.6 in./in./min , TESTED SEPTEMBER 1977

Sample ID	Average Area, in.^{2}	Ultimate Stress, σ_{ult}, ksi
1NH693- 7A	.0852	68.0
-20A	.0872	63.4
-26A	.0859	71.1
- 2B	.0871	66.5
-13B	.0882	66.1
-18B	.0887	68.0
-26B	.0862	72.9
-16C	.0878	71.0
-22C	.0874	70.4
-27C	.0861	65.0
Average		68.2

TABLE B21

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS (SAMPLE SIZE = 20)

Strain Rate = 0.015 in./in./min, Tested March 1976

Sample ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain ϵ_{ult}, in./in. in 2.0 in.	Apparent Modulus of Elasticity, E_2, psi x 10^6
727-29A	.1268	18670	147.2	.0095	15.5
8B	.1280	18760	146.6	.0099	14.8
10B	.1303	17800	136.6	.0086	15.9
32B	.1282	19300	150.5	.0092	16.4
12C	.1264	16860	133.4	.0088	15.2
728-30A	.1294	16790	129.8	.0081	16.0
21B	.1310	17620	134.5	.0082	16.4
35B	.1308	18360	140.4	.0093	15.1
29C	.1282	19060	148.7	.0098	15.2
36C	.1301	18320	140.8	.0090	15.6
696-14A	.1252	17680	141.2	.0095	14.9
15A	.1278	17830	139.5	.0098	14.4
31A	.1281	15200	118.7	.0065	18.3
24B	.1264	17200	136.1	.0101	13.5
25C	.1259	18300	145.4	.0094	15.5
699-2A a	.1257	18700	148.8	.0097	15.3
3B a	.1258	20360	161.8	.0098	16.5
27B	.1270	17320	136.4	.0097	14.1
15C	.1260	18600	147.6	.0099	14.9
30C	.1278	19190	150.2	.0101	14.5
Average			141.7 + 20.1 - 23.0	.0092 +.0009 -.0027	15.4 + 2.9 - 1.9

a - Coupon failed along a 45° angle

B23

TABLE B22

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS (SAMPLE SIZE = 30)
STRAIN RATE = 0.015 in./in./min, TESTED SEPTEMBER 1977

Sample ID	Average Area in.^{2}	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain e_{ult}, in./in. in 2.0 in.	Average Shape E_2, psi x 10^6
1NH727-10A	.1293	145.7	.0107	14.3
35A	.1298	144.7	.0103	14.6
26B	.1270	147.0	.0104	14.2
27B	.1267	146.0	.0104	13.8
29B	.1296	155.1	.0112	13.8
21C	.1306	140.5	.0099	14.1
32C	.1282	142.5	.0099	14.6
1NH728- 9A	.1304	142.7	.0104	14.0
16A	.1295	143.9	.0106	13.9
35A	.1311	137.8	.0100	13.9
33B	.1316	147.9	.0111	14.3
11C	.1301	145.1	.0106	14.2
26C	.1271	154.4	.0112	13.8
30C	.1287	154.1	.0105	14.6
37C	.1269	146.1	.0106	14.1
1NH696- 9B	.1295	141.0	.0102	13.7
33B	.1278	132.4	.0094	14.3
36B	.1251	137.8	.0094	14.5
20C	.1285	148.6	.0106	14.0
26C	.1239	135.1	.0098	13.8
27C	.1267	149.2	.0105	14.1
35C	.1289	130.4	.0090	14.6
1NH699- 5A	.1304	143.4	.0104	14.6
26A	.1261	150.1	.0103	14.7
2B	.1231	147.3	.0102	14.4
17B	.1286	148.3	.0099	14.9
20B	.1290	140.8	.0099	14.4
25B	.1275	134.4	.0099	14.2
32B	.1301	146.8	.0099	14.8
31C	.1288	129.1	.0088	14.6
Average		143.6	.0102	14.3

TABLE B23

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS (SAMPLE SIZE = 20)

STRAIN RATE ≈ 0.6 in./in./min, TESTED SEPTEMBER 1977

Sample ID	Average Area, in.^{2}	Ultimate Stress, σ_{ult}, ksi
1NH696-18A	.1292	146.9
-32A	.1275	137.6
-14B	.1262	121.3
-28B	.1291	126.4
- 7C	.1284	124.8
1NH699-12A	.1268	137.0
-24A	.1286	149.1
-36A	.1315	139.7
- 3C	.1267	138.4
- 9C	.1305	141.1
1NH727- 2A	.1240	146.5
-17A	.1296	132.3
-28A	.1264	132.1
- 5B	.1270	131.1
-18C	.1295	133.2
1NH728-14A	.1278	135.1
-19A	.1307	121.2
- 5B	.1292	125.2
-31B	.1302	139.1
-15C	.1303	141.4
Average		135.0

TABLE B24

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS (SAMPLE SIZE = 20)

STRAIN RATE $\cong$ 6.0 in./in./min, TESTED SEPTEMBER 1977

IN FATIGUE MACHINE

Sample ID	Average Area, in.^{2}	Ultimate Stress, σ_{ult}, ksi
1NH696- 1A	.1191	131.8
- 8A	.1283	127.5
-12A	.1232	109.4
-29B	.1292	126.7
- 8C	.1281	120.9
1NH699- 4A	.1292	143.4
-36B	.1279	129.6
- 2C	.1244	117.9
-12C	.1265	127.6
-16C	.1281	129.0
1NH727- 9A	.1281	142.5
-21B	.1292	156.8
-36B	.1276	145.6
-20C	.1294	139.4
-24C	.1282	124.7
1NH728-15B	.1289	115.2
-16B	.1290	117.9
-12C	.1278	112.7
-13C	.1294	116.4
-35C	.1311	124.0
Average		127.9

TABLE B25

TENSION TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS (SAMPLE SIZE = 19)

STRAIN RATE ≃ 0.013 in./in./min, TESTED OCTOBER 1977

IN FATIGUE MACHINE

Sample ID	Average Area, in.^{2}	Ultimate Stress, σ_{ult}, ksi
1NH696- 4B	.1283	143.0
-25B	.1274	129.1
-27B	.1280	143.6
- 1C	.1189	112.8
-22C	.1293	133.3
-32C	.1280	122.4
1NH699-13A	.1271	128.2
- 8B	.1313	117.9
-10B	.1328	133.6
-16B	.1272	136.2
1NH727-18A	.1292	138.2
-18B	.1281	132.3
-24B	.1298	147.7
-28B	.1279	124.4
1NH728- 3B	.1267	139.7
-17B	.1306	122.2
- 6C	.1296	132.3
-21C	.1332	153.2
-34C	.1310	142.1
Average		133.3

APPENDIX C

FATIGUE DATA

FATIGUE STRESS-LIFE

SCAN DATA

TABLE C1

STRESS-LIFE SCAN

TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS

Environment: Room Temperature, Laboratory Air

σ_{min} = 0 MPa (ksi), f = 10 Hz

Sample ID	Area, $mm^2(in.^2)$	Max. Stress, σ_{max}, MPa (ksi)	Cycles to Failure, N_F	Approximate Cycles to Delamination N_{DL}
2SF1117-C1	47.4 (.0734)	483 (70)	408	$-^a$
1SF1132-A14	47.9 (.0742)	483 (70)	757	$-^a$
1SF1117-C14	48.6 (.0754)	483 (70)	1139	$-^a$
2SF1132-A21	47.5 (.0736)	448 (65)	2935	$-^a$
1SF1121-A5	47.3 (.0733)	448 (65)	2173	$-^a$
2SF1132-A23	46.8 (.0725)	448 (65)	844	$-^a$
1SF1122-B4	47.4 (.0734)	414 (60)	7669	$-^b$
1SF1133-D32	47.5 (.0737)	414 (60)	5589	$-^b$
2SF1122-B1	47.1 (.0730)	414 (60)	5806	$-^b$
2SF1121-A31	48.0 (.0744)	379 (55)	13216	$-^b$
1SF1122-C12	46.8 (.0725)	379 (55)	12189	$-^b$
2SF1122-B25	48.3 (.0749)	379 (55)	4120	$-^b$
2SF1117-B5	49.0 (.0759)	345 (50)	49093	25000
1SF1121-A9	46.8 (.0726)	345 (50)	380721	47000
1SF1130-B31	48.0 (.0744)	345 (50)	73549	20000
1SF1133-C23	47.7 (.0740)	310 (45)	466010	205000
1SF1117-A11	47.6 (.0738)	310 (45)	867000	258000
2SF1130-B25	47.1 (.0730)	310 (45)	139479	$-^c$
2SF1130-B23	47.9 (.0743)	276 (40)	NF,^{d} 3 x 10^6	860000
2SF1117-B17	49.6 (.0769)	276 (40)	NF, 3 x 10^6	920000
2SF1130-D29	47.1 (.0730)	276 (40)	NF, 3 x 10^6	740000
1SF1130-C21	47.7 (.0739)	241 (35)	NF, 3 x 10^6	$-^e$
2SF1121-B9	48.3 (.0749)	241 (35)	NF, 3 x 10^6	$-^e$
1SF1132-A23	47.0 (.0728)	241 (35)	NF, 3 x 10^6	$-^e$

a - Delamination not observed prior to failure due to speed of test
b - Significant delamination not observed prior to failure
c - Cycles to delamination not recorded, technician error
d - NF - No fracture of the coupon
e - No delamination or other damage observed

C3

TABLE C2

STRESS-LIFE SCAN

TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS
Environment: Room Temperature, Laboratory Air

σ_{min} = -110 MPa (16.0 ksi), f = 10 Hz

Sample ID	Area $mm^2 (in.^2)$	Max. Stress, σ_{max}, MPa (ksi)	Cycles to Failure, N_F	Approximate Cycles to Delamination N_{DL}
1SF1122-D3	47.0 (.0728)	483 (70)	454	_a
1SF1122-C11	48.5 (.0752)	483 (70)	550	_a
1SF1132-A18	47.4 (.0735)	483 (70)	521	_a
2SF1121-D28	46.5 (.0721)	448 (65)	3050	_a
1SF1133-D13	47.7 (.0740)	448 (65)	1237	_a
1SF1130-B13	48.6 (.0754)	448 (65)	938	_a
1SF1132-C8	48.8 (.0756)	414 (60)	4895	_b
1SF1133-C14	47.5 (.0737)	414 (60)	3955	_b
2SF1130-D14	47.9 (.0742)	414 (60)	5060	_b
1SF1121-C29	48.1 (.0745)	379 (55)	7893	_b
2SF1122-B21	48.7 (.0755)	379 (55)	17220	_b
2SF1117-B20	50.0 (.0775)	379 (55)	14300	13000
1SF1117-C11	49.1 (.0761)	345 (50)	10860	_b
1SF1132-A11	46.5 (.0721)	345 (50)	10615	_b
1SF1121-C27	48.3 (.0749)	345 (50)	9800	_b
1SF1133-D9	47.0 (.0728)	310 (45)	61794	_b
1SF1130-C31	48.1 (.0745)	310 (45)	11500	_b
2SF1132-B13	47.9 (.0743)	310 (45)	22800	_b
2SF1122-B32	47.1 (.0730)	276 (40)	251228	77000
2SF1122-C11	47.9 (.0743)	276 (40)	87900	45000
2SF1121-C7	47.4 (.0734)	276 (40)	140327	107000
2SF1117-A30	46.9 (.0727)	241 (35)	305500	263000
1SF1117-B25	48.6 (.0753)	241 (35)	195600	140000
2SF1121-C30	47.2 (.0732)	241 (35)	201520	_c
2SF1130-D23	48.1 (.0745)	207 (30)	302300	>250000
1SF1130-C25	47.9 (.0742)	207 (30)	581500	>500000
2SF1130-B17	47.2 (.0732)	207 (30)	1150482[d]	699000

a - Delamination not observed prior to failure due to speed of test
b - Delamination not observed priot to failure
c - Delamination not observed prior to failure due to technician error
d - Severe delamination, but not fractured into two pieces

TABLE C3

STRESS-LIFE SCAN

TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS
Environment: 82.2°C (180°F), 90% R.H., Laboratory Air

σ_{min} = 0 MPa(ksi), f = 10 Hz
Average Moisture Content ~1.3%

Coupon ID	Area, mm^2	(in.^{2})	Maximum Stress σ_{max}, MPa	(ksi)	Cycles to Failure, N_F
1SF1130-C8	48.6	(.0754)	448	(65)	507
2SF1122-C30	47.4	(.0735)	448	(65)	1105
2SF117-A16	49.4	(.0766)	448	(65)	1464
1SF1130-A22	48.6	(.0753)	414	(60)	2042
1SF1121-D7	47.5	(.0737)	414	(60)	7755
2SF1132-A31	47.1	(.0730)	414	(60)	3720
2SF1122-D15	47.5	(.0737)	379	(55)	12706
2SF1132-D4	47.8	(.0741)	379	(55)	6716
2SF1130-B24	47.9	(.0742)	379	(55)	1958
1SF1132-C28	48.4	(.0750)	345	(50)	25490
2SF1130-A15	47.7	(.0740)	345	(50)	29567
SF1122-C25	48.4	(.0751)	345	(50)	3130[b]
1SF1117-A12	47.7	(.0740)	310	(45)	38340
1SF1133-C25	48.3	(.0749)	310	(45)	26889
2SF1130-D17	48.3	(.0749)	310	(45)	70943
1SF1132-A25	47.7	(.0740)	276	(40)	262293
1SF1132-B30	47.4	(.0734)	276	(40)	490077
2SF1121-C1	47.5	(.0737)	276	(40)	167347
1SF1121-C22	47.5	(.0736)	241	(35)	2086000 N.F.[a]
2SF1122-C15	48.4	(.0751)	241	(35)	3793000 N.F.
1SF1122-B14	48.9	(.0758)	241	(35)	1234000 N.F.
1SF1122-C5	48.1	(.0746)	207	(30)	1060000 N.F.
1SF1117-B3	48.4	(.0750)	207	(30)	1080000 N.F.
2SF1132-D23	47.7	(.0740)	207	(30)	1002000 N.F.

a - N.F. = No Failure

b - Coupon contained ~ 1.7% average moisture content

TABLE C4

STRESS-LIFE SCAN

TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS
Environment: 82.2°C (180°F), 90%, R.H., Laboratory Air

σ_{min} = -110 MPa(-16.0 ksi), f = 10 Hz

Average Moisture Content ~ 1.3%

Coupon ID	Area, mm^2	(in.^{2})	Maximum Stress σ_{max}, MPa	(ksi)	Cycles to Failure, N_F
1SF1130-A20	49.0	(.0760)	448	(65)	400
2SF1132-D11	48.2	(.0747)	448	(65)	610
2SF1121-B11	48.8	(.0756)	448	(65)	335[a]
2SF1132-D19	48.1	(.0745)	414	(60)	960
1SF1130-B14	48.9	(.0758)	414	(60)	970
1SF1122-C2	48.5	(.0752)	414	(60)	650[a]
2SF1130-B28	48.1	(.0745)	379	(55)	3450
2SF1130-B14	48.5	(.0751)	379	(55)	2190
2SF1122-D6	46.7	(.0724)	379	(55)	3613
1SF1133-C22	49.0	(.0759)	345	(50)	9540
1SF1122-A29	46.8	(.0726)	345	(50	4020
2SF1122-D11	48.4	(.0750)	345	(50)	2140[a]
1SF1121-B5	48.1	(.0745)	310	(45)	16938
1SF1133-B23	48.8	(.0756)	310	(45)	14340
2SF1117-C26	50.1	(.0776)	310	(45)	21000
2SF1122-A28	46.6	(.0723)	276	(40)	78903
2SF1117-B9	50.1	(.0776)	276	(40)	48906
1SF1130-A24	47.4	(.0735)	276	(40)	4462[a]
2SF1130-C2	47.4	(.0734)	241	(35)	60082
1SF1132-A27	47.0	(.0729)	241	(35)	111806
1SF1117-B15	49.7	(.0770)	241	(35)	210880
2SF1121-D1	46.8	(.0725)	207	(30)	181375
1SF1117-C2	49.4	(.0766)	207	(30)	213938
1SF1122-D16	48.6	(.0753)	207	(30)	105400

a - Coupon contained ~ 1.7% Average Moisture Content

TABLE C5

STRESS-LIFE SCAN

TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1 COUPONS

Environment: Room Temperature, Laboratory Air

$$\sigma_{min} = 0 \text{ MPa (ksi), } f = 10 \text{ Hz}$$

Sample ID	Gross Area, mm^2 $(in.^2)$	Gross[a] Max. Stress, σ_{max}, MPa (ksi)	Cycles to Failure N_F
1SF1130-B12	47.3 (.0733)	248 (36)	36
2SF1121-D17	48.0 (.0794)	248 (36)	165500
2SF1117-D6	48.6 (.0754)	248 (36)	104300
1SF1133-D20	48.0 (.0744)	234 (34)	1590
2SF1121-C16	47.9 (.0743)	234 (34)	265850
2SF1122-D25	45.5 (.0706)	234 (34)	22374
1SF1117-A31	48.8 (.0757)	221 (32)	483460
1SF1133-A23	47.2 (.0731)	221 (32)	837297
1SF1121-C1	46.6 (.0722)	221 (32)	274570
1SF1117-C18	49.9 (.0773)	207 (30)	771000
2SF1121-B16	48.2 (.0747)	207 (30)	NF,[b]1×10^6
1SF1132-A9	46.6 (.0722)	207 (30)	NF, 1×10^6
2SF1122-C10	48.1 (.0746)	193 (28)	NF, 1×10^6
1SF1130-A16	48.1 (.0745)	192 (28)	NF, 1×10^6
2SF1132-A30	47.0 (.0729)	193 (28)	NF, 1×10^6
2SF1130-D2	47.0 (.0729)	179 (26)	NF, 1×10^6
1SF1122-A15	47.7 (.0740)	179 (26)	NF, 1×10^6
2SF1130-A9	46.4 (.0719)	179 (26)	NF, 1×10^6

a - Stress based upon unnotched area
b - NF - No Fracture of the Coupon

C7

TABLE C6

STRESS-LIFE SCAN

TENSION-COMPRESSION RESULTS OF NOTCHED LAMINATE 1 COUPONS

Environment: Room Temperature, Laboratory Air

σ_{min} = -110 MPa (16 ksi), f = 10 Hz

Sample ID	Area mm^2 (in.^{2})	Gross[a] Max. Stress, σ_{max}, MPa (ksi)	Failure N_F
2SF1132-A13	46.9 (.0727)	248 (36)	6073
2SF1121-D32	46.6 (.0723)	248 (36)	6456
1SF1121-D6	46.6 (.0723)	248 (36)	8600
1SF1133-B22	49.0 (.0759)	234 (34)	6220
1SF1117-A19	49.1 (.0761)	234 (34)	11370
1SF1122-A19	46.6 (.0723)	234 (34)	13850
1SF1133-B19	47.7 (.0739)	221 (32)	27336
2SF1121-C4	46.9 (.0727)	221 (32)	36747
2SF1132-D18	47.2 (.0732)	221 (32)	9100
1SF1117-C16	49.2 (.0763)	207 (30)	34600
1SF1132-C13	47.0 (.0728)	207 (30)	26425
1SF1121-D26	47.5 (.0736)	207 (30)	33800
2SF1122-C17	48.5 (.0752)	193 (28)	51306
1SF1121-D3	48.2 (.0747)	193 (28)	35174
1SF1130-B4	48.3 (.0749)	193 (28)	65198
2SF1130-C3	46.9 (.0727)	179 (26)	97556
2SF1132-B6	47.7 (.0740)	179 (26)	120292
1SF1122-A11	46.3 (.0717)	179 (26)	167001
1SF1130-C18	47.4 (.0734)	165 (24)	199504
1SF1122-D11	46.9 (.0727)	165 (24)	284591
2SF1122-C28	48.1 (.0748)	165 (24)	210400
1SF1117-A1	46.6 (.0723)	152 (22)	108294
1SF1132-B9	48.1 (.0745)	152 (22)	201627
2SF1117-A25	48.1 (.0746)	152 (22)	86844
1SF1121-B10	48.2 (.0747)	138 (20)	123826
1SF1122-D22	47.2 (.0731)	138 (20)	302229
2SF1121-C19	47.9 (.0742)	138 (20)	165610
2SF1130-C13	46.6 (.0723)	124 (18)	59545
2SF1122-A30	46.7 (.0724)	124 (18)	898430
1SF1130-B21	47.9 (.0742)	124 (18)	297400
1SF1130-C13	48.1 (.0748)	110 (16)	462366
1SF1132-C2	47.1 (.0730)	110 (16)	1244468
1SF1133-B2	46.7 (.0724)	110 (16)	NF,[b] 2 x 10^6
2SF1121-A17	48.2 (.0747)	97 (14)	225000
2SF1130-C11	46.8 (.0726)	97 (14)	1833100
2SF1132-C20	47.7 (.0739)	97 (14)	NF, 2 x 10^6

a - Stress based upon Unnotched Area
b - NF - No Fracture of the coupon

C8

TABLE C7

STRESS-LIFE SCAN

TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1 COUPONS

Environment: 82.2°C (180°F), 90% R.H., Laboratory Air

σ_{min} = 0 MPa(ksi),   f = 10 Hz

Average Moisture Content ~ 1.5%

Coupon ID	Area, mm^2	(in.^{2})	Maximum Stress σ_{max}, MPa	(ksi)	Cycles to Failure, N_F
1SF1117-B22	49.9	(.0773)	348	(36)	4516
2SF1121-A28	48.3	(.0749)	348	(36)	3865
2SF1132-C10	48.4	(.0750)	348	(36)	4140
1SF1130-C17	48.5	(.0751)	234	(34)	10651
1SF1133-B25	48.2	(.0747)	234	(34)	4917
1SF1132-D16	48.4	(.0750)	234	(34)	11499
2SF1117-C29	48.0	(.0744)	221	(32)	43160
2SF1130-A31	47.1	(.0730)	221	(32)	29762
1SF1117-B12	48.7	(.0755)	221	(32)	8293[a]
1SF1122-D1	45.9	(.0711)	207	(30)	70700
2SF1122-A29	46.5	(.0720)	207	(30)	82477
2SF1117-C12	49.0	(.0760)	207	(30)	21293
2SF1117-C5	48.8	(.0757)	193	(28)	154787
1SF1133-C12	47.7	(.0739)	193	(28)	43395
1SF1121-D27	48.1	(.0745)	193	(28)	427500[a]
2SF1122-C9	46.4	(.0720)	165	(24)	496340[a]
1SF1122-B6	46.4	(.0718)	165	(24)	N.F.[a,b]
2SF1121-A9	49.5	(.0767)	165	(24)	N.F.[a]
2SF1130-B10	48.4	(.0750)	138	(20)	N.F.[a]
1SF1130-A26	47.9	(.0743)	138	(20)	N.F.[a]

a - Coupon contained ~ 1.7% average moisture content

b - N.F. indicates no fracture of the coupon at 10^6 cycles

TABLE C8

TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1 COUPONS

Environment: 82.2°C (180°F), 90% R.H., Laboratory Air

σ_{min} = -110 MPa(-16 ksi), f = 10 Hz

Average Moisture Content ~ 1.5%

Coupon ID	Area mm^2	(in.^{2})	Maximum Stress σ_{max}, MPa	(ksi)	Cycles to Failure, N_F
1SF1132-A29	47.2	(.0732)	348	(36)	1530
2SF1130-C7	48.6	(.0754)	348	(36)	1200
1SF1121-D31	47.9	(.0743)	348	(36)	1199
2SF1121-B1	45.7	(.0708)	234	(34)	882
1SF1130-B3	48.6	(.0753)	234	(34)	3200
1SF1122-B7	47.0	(.0743)	234	(34)	2772
2SF1122-C21	48.0	(.0744)	221	(32)	5864
1SF1133-B5	48.3	(.0749)	221	(32)	3100
1SF1117-A18	48.7	(.0755)	221	(32)	3409
2SF1117-C24	48.0	(.0744)	207	(30)	3240
1SF1132-D10	46.5	(.0721)	207	(30)	6630
1SF1121-C26	48.0	(.0744)	207	(30)	5920
2SF1121-A3	49.7	(.0770)	197	(28)	4230
2SF1130-B30	47.9	(.0743)	193	(28)	14202
2SF1132-A4	47.3	(.0733)	193	(28)	5123[a]
1SF1122-C26	49.1	(.0761)	179	(26)	12951
2SF1122-D27	47.1	(.0730)	179	(26)	21617[a]
1SF1133-B14	49.8	(.0772)	179	(26)	6733
1SF1117-B6	49.8	(.0772)	165	(24)	14260[b]
1SF1133-C31	47.9	(.0742)	165	(24)	-
1SF1117-C19	49.7	(.0771)	165	(24)	8685[a]
2SF1117-C14	40.3	(.0780)	152	(22)	25453
1SF1132-C13	48.3	(.0749)	152	(22)	28600
2SF1121-A30	48.4	(.0750)	138	(20)	34699
1SF1122-B21	47.9	(.0742)	138	(20)	24718
2SF1130-D4	48.0	(.0744)	138	(20)	31000
2SF1122-D1	46.7	(.0724)	124	(18)	14100
2SF1130-C10	48.7	(.0755)	124	(18)	24880
1SF1130-B22	49.2	(.0763)	124	(18)	43469
1SF1133-C26	49.3	(.0764)	110	(16)	521800
2SF1132-B21	48.8	(.0756)	110	(16)	137469
1SF1132-C16	49.0	(.0760)	110	(16)	41740

a - Coupon had ~ 1.7% average moisture content
b - Test coupon failed by hydraulic or electrical malfunction.

TABLE C9

STRESS-LIFE SCAN

TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS

Environment: Room Temperature, Laboratory Air

$$\sigma_{min} = 0 \text{ MPa (ksi)}, \ f = 10 \text{ Hz}$$

Sample ID	Area, mm^2 $(in.^2)$	Max. Stress, σ_{max}, MPa (ksi)	Cycles to Failure, N_F
2SF1133-A19	67.9 (.1052)	965 (140)	1
2SF1133-C23	67.2 (.1042)	896 (130)	1
1SF1137-C12	68.8 (.1066)	827 (120)	122
1SF1149-D25	65.7 (.1019)	827 (120)	NF,[a] 1×10^6
1SF1137-D14	71.9 (.1115)	827 (120)	294
2SF1137-D1	68.3 (.1058)	758 (110)	889257
1SF1137-C17	71.2 (.1104)	758 (110)	10853
2SF1137-D30	76.3 (.1182)	758 (110)	3980
2SF1137-A29	69.4 (.1075)	689 (100)	NF, 3×10^6
1SF1149-D6	67.8 (.1051)	689 (100)	NF, 2×10^6
2SF1149-C25	69.3 (.1074)	689 (100)	NF, 3×10^6
2SF1133-D2	69.1 (.1071)	621 (90)	NF, 1×10^6
1SF1149-C18	67.5 (.1046)	621 (90)	NF, 1×10^6
2SF1133-B11	68.7 (.1065)	552 (80)	NF, 1×10^6
1SF1149-D23	69.5 (.1077)	552 (80)	NF, 1×10^6

a - NF - No Fracture of the Coupon

TABLE C10

STRESS-LIFE SCAN

TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS

Environment: Room Temperature, Laboratory Air

σ_{min} = -207 MPa (30.0 ksi), f=10 Hz

Sample ID	Area, mm^2 ($in.^2$)	Max. Stress, σ_{max}, MPa (ksi)	Cycles to Failure, N_F
2SF1133-D20	69.5 (.1077)	896 (130)	20
2SF1149-D9	71.0 (.1101)	896 (130)	28
1SF1149-B30	68.6 (.1063)	896 (130)	43
2SF1137-A24	68.3 (.1058)	827 (120)	620
1SF1149-B21	71.3 (.1105)	827 (120)	593600
1SF1137-D19	70.8 (.1098)	827 (120)	402
1SF1149-B31	70.0 (.1085)	758 (110)	NF,[a] 1 x 10^6
1SF1137-B18	68.5 (.1062)	758 (110)	654400
2SF1137-D23	69.8 (.1082)	758 (110)	394449
1SF1137-C23	71.6 (.1110)	689 (100)	NF, 1 x 10^6
1SF1149-B24	68.5 (.1062)	689 (100)	23471
1SF1137-D25	69.5 (.1078)	689 (100)	NF, 1 x 10^6
2SF1149-A23	70.8 (.1097)	621 (90)	NF, 1 x 10^6
2SF1149-D19	70.8 (.1097)	621 (90)	NF, 1 x 10^6
2SF1133-D27	67.7 (.1049)	621 (90)	NF, 1 x 10^6
2SF1133-A29	66.6 (.1033)	552 (80)	NF, 1 x 10^6
2SF1149-C10	71.7 (.1111)	552 (80)	NF, 1 x 10^6
2SF1133-C28	69.7 (.1080)	552 (80)	NF, 1 x 10^6

a - NF = No Fracture of the Coupon

TABLE C11

STRESS-LIKE SCAN

TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS

Environment: 82.2°C (180°F), 90% R.H., Laboratory Air

$$\sigma_{min} = 0 \text{ MPa(ksi)}, \quad f = 10 \text{ Hz}$$

Average Moisture Content ~ 1.3%

Coupon ID	Area,		Maximum Stress σ_{max},		Cycles to Failure
	mm^2	$(in.^2)$	MPa	(ksi)	
2SF1149-D22	72.7	(.1127)	896	(130)	569 [b]
1SF1137-B9	73.5	(.1140)	896	(130)	270 [b]
2SF1133-A10	68.1	(.1055)	896	(130)	940 [b]
1SF1149-B1	67.0	(.1039)	827	(120)	679332
1SF1137-C6	70.3	(.1090)	827	(120)	4650
2SF1149-D13	70.0	(.1085)	827	(120)	435370
1SF1149-C19	69.0	(.1070)	758	(110)	10^6 N.F. [a]
2SF1149-A22	76.1	(.1118)	758	(110)	975800
2SF1137-C17	70.5	(.1093)	758	(110)	1091798
1SF1149-B6	68.3	(.1058)	689	(100)	10^6 N.F.
2SF1149-C16	70.9	(.1099)	689	(100)	10^6 N.F. [b]
2SF1133-A15	71.0	(.1101)	689	(100)	10^6 N.F. [b]
1SF1149-C15	71.0	(.1100)	621	(90)	10^6 N.F.
2SF1149-D8	71.3	(.1105)	621	(90)	10^6 N.F.
2SF1133-A16	70.3	(.1089)	621	(90)	10^6 N.F.
2SF1137-C21	72.3	(.1121)	621	(90)	598500
2SF1133-A13	68.8	(.1067)	552	(80)	10^6 N.F.
1SF1137-C19	69.5	(.1078)	552	(80)	10^6 N.F.
2SF1137-C29	70.8	(.1098)	552	(80)	10^6 N.F.

a - N.F. = No Failure.

b - Coupon had ~ 1.7% average moisture

TABLE C12

STRESS-LIFE SCAN

TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS

Environment: 82.2°C (180°F), 90% R.H., Laboratory Air

σ_{min} = -207 MPa   (30.0 ksi),   f = 10 Hz

Average Moisture Content $\sim$ 1.3%

Coupon ID	Area		Max. Stress, σ_{max}, MPa (ksi)		Cycles to Failure, N_F
	mm^2	(in.^{2})			
1SF1137-B2	71.1	(.1102)	896	*130)	54
1SF1149-A12	66.8	(.1036)	896	(130)	60
2SF1137-C12	70.6	(.1094)	827	(120)	180
2SF1149-C24	69.2	(.1072)	827	(120)	1032
1SF1149-D12	68.1	(.1055)	827	(120)	915
2SF1149-B18	66.0	(.1023)	758	(110)	1719
2SF1133-C31	68.1	(.1056)	758	(110)	145500
1SF1149-D29	69.2	(.1072)	758	(110)	39350
2SF1137-A16	72.1	(.1117)	689	(100)	124900
1SF1149-B9	72.5	(.1124)	689	(100)	173010
1SF1137-A11	71.3	(.1105)	689	(100)	96185
1SF1149-B16	71.3	(.1105)	621	(90)	44640
2SF1133-B3	69.4	(.1076)	552	(80)	10^6 N.F.
2SF1137-C22	71.5	(.1109)	552	(80)	10^6 N.F.
1SF1149-A15	72.6	(.1125)	552	(80)	10^6 N.F.[a,b]

a - N.F. = No fracture of the coupon
b - Coupon had $\sim$ 1.7% Average Moisture Content

FATIGUE SCATTER
DATA FOR UN-NOTCHED
COUPONS

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TABLE C13

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT MAXIMUM STRESS OF 207 MPa (30 ksi)
AT 82.2°C (180°F), 90% R.H. in Laboratory Air

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A15	49.8 (.0772)	NF [a]
-B3	48.4 (.0750)	NF [b]
2SF1117-A3	49.6 (.0769)	NF
-C15	50.5 (.0783)	820,000
1SF1121-B1	46.1 (.0714)	NF
-D1	46.2 (.0716)	NF
2SF1121-C18	48.9 (.0758)	NF
-D10	48.3 (.0748)	NF
1SF1122-C5	48.1 (.0746)	NF [b]
2SF1122-D12	46.1 (.0714)	NF
1SF1130-C1	47.8 (.0741)	568,105
2SF1130-B18	47.9 (.0742)	NF
1SF1132-A7	47.0 (.0728)	NF
2SF1132-D23	47.7 (.0740)	NF [b]
1SF1133-C7	48.6 (.0754)	NF

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"

b - Coupon had ~ 1.3% Average Moisture Content

TABLE C14

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT MAXIMUM STRESS OF 276MPa (40 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = 0.0$ MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-C20	50.3 (.0779)	1,010,000 NF
2SF1117-B8	50.8 (.0787)	218,280
1SF1121-D14	46.1 (.0714)	NF [a]
2SF1121-C1	47.5 (.0737)	167,347 [b]
1SF1122-A10	47.6 (.0738)	NF
-A17	48.1 (.0746)	442,160
2SF1122-B3	48.4 (.0750)	119,170
-B11	47.9 (.0743)	237,500
1SF1130-C9	49.5 (.0767)	336,070
-D5	48.4 (.0750)	33,540
2SF1132-D23	49.4 (.0766)	158,364
1SF1132-B30	47.4 (.0734)	490,077 [b]
-C6	48.5 (.0752)	96,410
2SF1132-B5	47.7 (.0739)	912,180
1SF1133-A25	47.7 (.0740)	262,293 [b]

a - NF = No Failure at 1×10^6 cycles, defined as "run out"

b - Coupon had ~ 1.3% Average Moisture Content

TABLE C15

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT MAXIMUM STRESS OF 345 MPa (50 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 ($in.^2$)	Cycles to Failure, N_f
2SF1117-B27	51.0 (.0791)	8,624
1SF1121-C7	48.1 (.0746)	9,210
2SF1121-D9	47.7 (.0739)	15,520
1SF1122-C25	48.5 (.0751)	3,180
1SF1130-C29	49.8 (.0772)	4,550
2SF1130-A13	46.8 (.0725)	4,955
-A15	47.7 (.0740)	29,567[a]
1SF1132-C15	48.5 (.0752)	11,120
-C28	48.4 (.0750)	25,490[a]
2SF1132-C9	49.2 (.0763)	32,000
-C11	48.3 (.0749)	7,068
1SF1133-A31	48.3 (.0748)	2,130
-D1	51.3 (.0795)	21,211
2SF1132-C27	49.0 (.0760)	9,538

a - Coupon had ~ 1.3% Average Moisture Content

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TABLE C16

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT MAXIMUM STRESS OF 414 MPa (60 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A24	47.8 (.0741)	123
-B8	49.9 (.0774)	1,102
2SF1117-A8	48.8 (.0756)	1,350
-C18	49.4 (.0766)	829 [a]
1SF1121-D7	47.5 (.0737)	7,755
-D30	47.3 (.0733)	1,018
2SF1121-D2	48.1 (.0745)	730
-D22	48.5 (.0752)	760
1SF1122-B2	48.2 (.0747)	1,503
2SF1122-C26	48.2 (.0747)	560
1SF1130-A22	48.6 (.0753)	2,042 [a]
2SF1130-B26	47.5 (.0737)	557
1SF1132-A28	47.2 (.0731)	1,235
2SF1132-A31	47.1 (.0730)	3,720 [a]
-C26	49.0 (.0760)	1,130
1SF1133-C20	48.5 (.0752)	784

a - Coupon had ~ 1.3% Average Moisture Content

TABLE C17

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 138 MPa (20 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = -110$ MPa (-16.0 ksi)

Average Moisture Content $\sim 1.7\%$

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A5	49.5 (.0767)	NF [a]
2SF1117-A4	49.9 (.0774)	226,000
-A20	50.1 (.0777)	NF [b]
-A27	49.2 (.0763)	NF [b]
-B18	49.8 (.0772)	NF [b]
-B21	50.8 (.0787)	NF [b]
-C30	50.1 (.0776)	NF [b]
-C32	49.7 (.0771)	NF [b]
1SF1122-A12	47.4 (.0734)	369,984
-B8	49.2 (.0763)	NF [b]
-C16	48.7 (.0755)	NF [a]
2SF1122-A17	47.8 (.0741)	NF [a]
1SF1132-C29	48.2 (.0747)	NF [a]
2SF1132-B7	48.5 (.0752)	272,200
1SF1132-B12	48.5 (.0751)	NF [a]

a - NF = No Failure at 1×10^6 cycles, defined as "run out"

b - NF = No Failure at 5×10^5 cycles, defined as "run out"

TABLE C18

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 207 MPa (30 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-16.0 ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-C2	49.4 (.0766)	213,938[a]
2SF1117-B16	51.0 (.0790)	42,135
1SF1121-A24	47.5 (.0737)	47,640
2SF1121-B25	48.6 (.0753)	33,490
-D1	46.8 (.0725)	181,375[a]
1SF1122-C24	47.3 (.0733)	49,990
-D16	48.6 (.0753)	105,400[a]
-D21	48.1 (.0745)	86,300
2SF1122-A23	49.1 (.0761)	77,032
1SF1130-C24	48.5 (.0752)	24,820
-D32	49.3 (.0764)	32,675
2SF1130-D9	47.2 (.0732)	50,289
1SF1132-B13	49.2 (.0762)	64,207
2SF1132-B9	48.7 (.0755)	76,782
1SF1133-C10	49.4 (.0765)	60,898
-D7	47.7 (.0739)	13,200

a - Coupon had ~ 1.3% Average Moisture Content

TABLE C19

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 276 MPa (40 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-16.0 ksi)

Average Moisture Content $\sim$ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A17	50.3 (.0780)	6,613
2SF1117-B9	50.1 (.0776)	48,906[a]
1SF1121-D8	47.8 (.0741)	31,600
2SF1121-B27	49.4 (.0766)	8,280
1SF1122-A28	46.6 (.0723)	78,903[a]
2SF1122-B13	48.2 (.0747)	8,140
1SF1130-A24	47.4 (.0735)	4,462
-D29	48.4 (.0750)	10,085
2SF1130-A7	46.3 (.0718)	8,450
-A23	48.0 (.0744)	3,770
1SF1132-B18	47.2 (.0732)	12,278
-C21	49.0 (.0760)	13,860
2SF1132-A15	49.0 (.0759)	11,860
-C5	47.7 (.0739)	9,009
-C24	48.3 (.0749)	4,099

a - Coupon had $\sim$ 1.3% Average Moisture Content

TABLE C20

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 345 MPa (50 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz
$\sigma_{min} = -110$ MPa (-16.0 ksi)

Average Moisture Content $\sim$ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-B4	49.7 (.0771)	1,330
-C24	48.3 (.0748)	1,250
2SF1117-B12	48.7 (.0755)	1,041
1SF1121-D23	47.9 (.0742)	2,850
1SF1122-A22	48.3 (.0749)	5,850
-A29	46.8 (.0726)	4,020 [a]
2SF1122-D11	48.4 (.0750)	2,140
1SF1130-C3	48.3 (.0749)	2,080
-D22	49.4 (.0766)	1,500
2SF1130-B2	47.3 (.0733)	2,959
-C32	48.5 (.0752)	1,720
1SF1132-B12	47.7 (.0739)	2,300
-C17	48.7 (.0755)	2,548
1SF1133-C2	49.0 (.0759)	9,540 [a]

a - Coupon had $\sim$ 1.3% Average Moisture Content

TABLE C21

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF Un-NOTCHED LAMINATE 2
COUPONS TESTED AT A MAXIMUM STRESS OF 689 MPa (100 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content $\sim$ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
2SF1133-A15	71.0 (.1101)	NF[a,b]
-A23	68.2 (.1057)	NF
-B4	68.8 (.1066)	NF
-B28	70.8 (.1097)	NF
-C7	69.4 (.1075)	NF
-C14	69.7 (.1080)	NF
-C24	78.0 (.1209)	103,702
-D11	67.7 (.1049)	NF
-D23	66.4 (.1029)	NF
1SF1137-A10	72.1 (.1118)	NF
-B15	73.8 (.1144)	NF
-B24	70.8 (.1098)	794,360
-C22	71.5 (.1109)	NF
-D4	74.1 (.1149)	NF
-D23	71.2 (.1104)	NF
-D26	70.5 (.1093)	NF
2SF1137-A5	71.4 (.1106)	NF
-A15	72.3 (.1121)	NF
-B3	72.6 (.1125)	NF
-B30	69.4 (.1076)	168,000
-C2	71.6 (.1110)	NF
-C11	72.4 (.1122)	NF
-D4	70.7 (.1096)	NF
-D9	70.6 (.1094)	NF
-D19	71.7 (.1112)	NF
1SF1149-A16	72.6 (.1125)	NF
-B6	68.3 (.1058)	NF[b]
-B10	72.2 (.1119)	NF
-C6	68.8 (.1067)	NF
-C10	72.5 (.1124)	NF
-C17	69.9 (.1083)	NF
-D27	70.6 (.1095)	NF

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"
b - Coupon had $\sim$ 1.3% Average Moisture Content

TABLE C21   (Continued)

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2
COUPONS TESTED AT A MAXIMUM STRESS OF 689 MPa (100 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f - 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
2SF1149-A11	68.9 (.1068)	NF[a]
-B4	71.4 (.1107)	NF
-B31	76.8 (.1190)	NF
-C8	72.5 (.1124)	NF
-C16	70.9 (.1099)	NF
-C18	68.5 (.1062	NF
-D4	73.1 (.1133)	NF
-D21	72.8 (.1128)	NF

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"

TABLE C22

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2
COUPONS TESTED AT A MAXIMUM STRESS OF 827 MPa (120 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
2SF1133-C2	67.4 (.1054)	106,932
-D4	68.6 (.1063)	214,594
-D15	70.3 (.1089)	16,000
1SF1137-A9	71.4 (.1106)	5,550
-A13	71.8 (.1113)	22,635
-B16	72.3 (.1120)	642,480
-B23	72.2 (.1119)	13,670
-C6	70.3 (.1090)	4,650[b]
-D22	73.7 (.1143)	731,697
2SF1137-A7	71.2 (.1103)	31,565
-B11	72.0 (.1116)	61,170
-D5	71.5 (.1108)	NF[a]
-D20	72.5 (.1123)	100,250
1SF1149-A3	73.8 (.1144)	9,165
-B1	67.0 (.1039)	679,332[b]
-B7	70.2 (.1088)	44,180
-D10	69.8 (.1082)	142,420
2SF1149-B11	71.9 (.1115)	237,421
-C9	73.3 (.1136)	403,535
-C19	70.6 (.1095)	62,260
-D13	70.0 (.1085)	435,370[b]

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"

b - Coupon had ~ 1.3% Average Moisture Content

TABLE C23

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2
COUPONS TESTED AT A MAXIMUM STRESS OF 552 MPa (80 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-30.0 ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 ($in.^2$)	Cycles to Failure, N_f
2SF1133-A29	66.6 (.1033)	NF[a]
-C28	69.7 (.1080)	NF
-D22	69.7 (.1081)	NF
-D24	64.8 (.1005)	NF
-D30	67.2 (.1041)	NF
1SF1137-A16	71.0 (.1100)	NF
-B27	73.5 (.1139)	NF
-D27	71.4 (.1106)	NF
2SF1137-B21	72.8 (.1129)	NF[b]
-C25	72.4 (.1122)	NF
-D8	70.9 (.1099)	NF
1SF1149-A15	72.6 (.1125)	NF
-A17	72.7 (.1127)	NF
-B12	69.4 (.1076)	NF
-C25	67.8 (.1051)	NF
-D20	72.3 (.1120)	NF
-D22	72.6 (.1126)	NF
-D30	69.7 (.1080)	12,800
2SF1149-A32	73.0 (.1131)	238,045
-B28	72.8 (.1129)	NF
-C10	71.7 (.1111)	NF
-D27	70.8 (.1098)	NF

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"

b - Excessive delamination

TABLE C24

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 2
COUPONS TESTED AT A MAXIMUM STRESS OF 689 MPa (100 ksi) AT
82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = -110$ MPa $(-30.0$ ksi$)$

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 $(in.^2)$	Cycles to Failure, N_f
2SF1133-A21	70.8 (.1097)	407,249
-B13	69.4 (.1076)	213,315
-B17	67.8 (.1051)	12,744
1SF1137-A11	71.3 (.1105)	96,185[b]
-B16	72.3 (.1120)	642,480
-B1ᶜ	71.2 (.1103)	123,115
-C23	71.6 (.1110)	NF [a,c]
-D6	70.4 (.1091)	18,092
-D10	72.5 (.1124)	196,210
-D25	69.5 (.1078)	NF
2SF1137-A16	72.1 (.1117)	124,290[b]
-B13	73.5 (.1140)	40,370
-D14	72.5 (.1123)	259,400
-D25*	70.5 (.1093)	6,521
1SF1149-B9	72.5 (.1124)	173,010[b]
-B24	68.5 (.1062)	23,471
-C27	70.6 (.1094)	834
-D24	68.5 (.1061)	93,200

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"

b - Coupon had ~ 1.3% Average Moisture Content

c - Shredded severely

FATIGUE SCATTER

DATA FOR NOTCHED

LAMINATE 1 COUPONS

TABLE C25

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 179 MPa (26 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = 0.0$ MPa (ksi)

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-C27	48.0 (.0744)	NF[a]
2SF1117-B29	49.5 (.0768)	NF
1SF1121-A2	48.0 (.0744)	NF
2SF1121-B8	48.8 (.0757)	NF
1SF1122-A15	47.7 (.0740)	NF
-D24	45.7 (.0709)	NF
2SF1122-B16	47.8 (.0741)	NF
-B31	47.0 (.0729)	NF
1SF1130-B9	48.1 (.0745)	NF
-D10	47.4 (.0734)	NF
2SF1130-A9	46.4 (.0719)	NF
1SF1132-C4	47.1 (.0730)	NF
2SF1132-C22	48.4 (.0750)	NF
1SF1133-B20	47.9 (.0742)	NF
-D15	48.4 (.0750)	NF

a - NF = No Failure at 1×10^6 cycles,
defined as "run-out"

TABLE C26

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 207 MPa (30 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-C18	49.9 (.0773)	771,000
2SF1117-C22	47.8 (.0741)	NF [a]
1SF1121-C13	47.7 (.0739)	540,816
2SF1121-B16	48.2 (.0747)	NF
2SF1122-B23	48.1 (.0746)	NF
-D23	46.8 (.0726)	843,080
2SF1122-D30	45.4 (.0704)	NF
1SF1130-A4	48.2 (.0747)	NF
-B27	48.5 (.0752)	NF
2SF1130-D26	47.1 (.0730)	NF
1SF1132-A9	46.6 (.0722)	NF
-C20	48.3 (.0748)	NF
2SF1132-C3	47.4 (.0734)	NF
1SF1133-C2	47.6 (.0738)	NF
-C5	47.7 (.0739)	NF

a - NF = No Failure at 1 x 10^6 cycles, defined as "run out"

TABLE C27

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULT OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 234 MPa (34 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Coupon ID	Area mm^2 $(in.^2)$	Cycles to Failure, N_f
1SF1117-B18	48.6 (.0753)	119,499
2SF1117-C20	49.0 (.0759)	159,136
1SF1121-D32	46.8 (.0725)	620,000
2SF1121-A23	49.0 (.0760)	141,320
-C16	47.9 (.0743)	265,850
1SF1122-D8	47.2 (.0732)	492,198
2SF1122-B14	47.7 (.0739)	215,549
-D25	45.5 (.0706)	22,374
1SF1130-A5	48.1 (.0746)	132,330
-B16	48.0 (.0744)	159,401
2SF1130-C22	48.0 (.0744)	149,470
1SF1132-C31	46.8 (.0725)	296,396
2SF1132-A26	46.6 (.0723)	270,930
-D12	46.8 (.0726)	152,249
1SF1133-D20	48.0 (.0744)	1,590

TABLE C28

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 248 MPa (36 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A8	48.3 (.0740)	78,602
2SF1117-B15	49.5 (.0768)	82,928
-D6	48.6 (.0754)	104,300
1SF1121-A26	46.8 (.0726)	183,280
-D25	46.8 (.0726)	114,692
2SF1121-D17	48.0 (.0744)	165,500
1SF1122-B16	48.6 (.0754)	154,040
-B24	47.6 (.0736)	470
2SF1122-B4	47.3 (.0733)	207,708
1SF1130-B12	47.3 (.0733)	36
2SF1130-B8	47.4 (.0735)	120,371
-C15	47.9 (.0743)	7,190
1SF1132-B20	47.2 (.0732)	211,900
2SF1132-D9	47.6 (.0738)	243,330
1SF1133-A15	48.3 (.0749)	90,647

TABLE C29

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 110 MPa (16 ksi) AT
ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-16 ksi)

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A4	48.4 (.0750)	433,080
2SF1117-B19	49.2 (.0763)	1,165,700
-C10	49.8 (.0772)	749,465
1SF1121-C4	47.5 (.0736)	583,985
2SF1121-C25	47.2 (.0732)	715,119
-D3	47.7 (.0739)	1,464,345
1SF1122-A23	47.4 (.0734)	1,144,134
-B15	47.5 (.0736)	981,308
1SF1130-C13	48.3 (.0748)	462,366
2SF1130-B19	45.9 (.0712)	1,165,700
-C18	47.2 (.0732)	1,130,500
1SF1132-C2	47.1 (.0730)	1,244,468
2SF1132-A1	45.7 (.0708)	1,638,306
1SF1133-A22	47.8 (.0741)	222,155
-B26	48.3 (.0749)	2,860,206

TABLE C30

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 152 MPa (22 ksi) AT
ROOM TEMPERATURE IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = -110$ MPa $(-16$ ksi$)$

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A1	46.6 (.0723)	108,294
2SF1117-A25	48.1 (.0746)	86,844
1SF1121-A8	47.1 (.0730)	416,259
2SF1121-D18	47.2 (.0732)	144,361
1SF1122-B18	47.4 (.0734)	340,267
-D15	47.7 (.0739)	283,940
2SF1122-A15	47.7 (.0740)	405,707
-C4	46.7 (.0724)	321,132
1SF1130-A7	46.7 (.0731)	160,746
2SF1130-A2	47.2 (.0732)	109,328
1SF1132-A10	46.6 (.0722)	289,571
-B9	48.1 (.0745)	201,627
2SF1132-A28	46.3 (.0718)	350,213
-B4	46.3 (.0718)	291,556
1SF1133-A14	46.6 (.0723)	759,310

TABLE C31

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 193 MPa (28 ksi) AT
ROOM TEMPERATURE IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = -110$ MPa $(-16$ ksi$)$

Coupon ID	Area mm^2 $(in.^2)$	Cycles to Failure, N_f
1SF1117-A22	48.7 (.0755)	55,492
2SF1117-A31	49.0 (.0760)	19,905
1SF1121-D3	48.2 (.0747)	35,174
-D17	47.1 (.0730)	61,167
2SF1121-B17	47.9 (.0743)	16,975
1SF1122-B3	46.3 (.0717)	93,591
2SF1122-C2	47.6 (.0738)	72,014
-C17	48.5 (.0752)	51,306
1SF1130-B4	48.3 (.0749)	65,198
-C5	48.6 (.0754)	24,471
2SF1130-D30	47.0 (.0728)	34,660
1SF1132-B27	47.7 (.0740)	148,361
2SF1132-B18	46.5 (.0721)	90,000
-C23	47.4 (.0734)	35,487
1SF1133-D19	47.5 (.0737)	69,670

TABLE C32

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 234 MPa (34 ksi) AT
ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-16 ksi)

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A19	49.1 (.0761)	11,370
2SF1117-A26	48.3 (.0749)	5,842
1SF1121-A10	47.4 (.0735)	12,210
-C15	48.7 (.0755)	15,485
2SF1121-C3	47.1 (.0730)	23,549
1SF1122-A19	46.6 (.0723)	13,850
2SF1122-C5	46.5 (.0721)	21,980
1SF1130-B6	48.2 (.0747)	10,726
-B7	48.2 (.0747)	10,493
2SF1130-B9	47.5 (.0737)	9,225
-D1	43.9 (.0681)	5,601
1SF1132-D10	46.5 (.0720)	9,654
2SF1132-C19	47.1 (.0730)	18,777
-C32	47.6 (.0738)	16,241
1SF1133-B22	49.1 (.0759)	6,220
-C28	48.1 (.0746)	10,586

TABLE C33

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 165 MPa (24 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A29	49.2 (.0762)	513,482
-B28	49.8 (.0772)	626,650
2SF1117-B4	49.8 (.0772)	852,100
-C27	51.0 (.0790)	NF[a]
1SF1121-A25	47.0 (.0729)	NF
1SF1121-C20	48.9 (.0758)	NF
-D4	48.5 (.0752)	172,651
2SF1121-A4	49.5 (.0767)	NF
-A25	47.8 (.0741)	473,140
1SF1122-B6	46.4 (.0719)	NF
2SF1122-C9	46.5 (.0720)	496,340
1SF1130-D15	49.9 (.0774)	NF
2SF1130-B32	47.9 (.0742)	NF
1SF1132-C7	48.3 (.0748)	947,040
2SF1132-A17	47.9 (.0742)	571,900

a - NF, No Failure at 1×10^6 cycles, defined as "run out"

TABLE C34

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 193 MPa(28 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = 0.0$ MPa (ksi)

Average Moisture Content $\sim 1.7\%$

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A9	48.8 (.0757)	99,670
2SF1117-C5	48.8 (.0757)	154,787 [a]
1SF1121-D27	48.1 (.0745)	427,500
2SF1121-C27	49.0 (.0759)	59,870
1SF1122-A2	47.2 (.0732)	102,290
-C6	48.0 (.0744)	130,270
2SF1122-A3	48.1 (.0745)	86,547
-B6	48.3 (.0748)	96,752
1SF1130-C16	49.5 (.0767)	71,150
-D12	47.4 (.0735)	47,932
2SF1130-C9	49.0 (.0760)	12,360
-D13	47.4 (.0734)	68,855
1SF1132-A20	48.6 (.0750)	170,100
2SF1132-B11	48.8 (.0757)	58,470
1SF1133-C12	47.7 (.0739)	43,395 [a]

a - Coupon had $\sim 1.5\%$ Average Moisture Content

TABLE C35

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 221 MPa (32 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = 0.0 MPa (ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})		Cycles to Failure, N_f
1SF1117-B12	48.7	(.0755)	8,293
-B30	48.7	(.0755)	12,749
2SF1117-C29	48.0	(.0744)	48,160[a]
1SF1121-A3	48.8	(.0757)	28,230
2SF1121-A26	47.8	(.0741)	21,680
1SF1122-C21	48.0	(.0744)	27,440
2SF1122-B5	47.5	(.0736)	20,531
1SF1130-B16	48.4	(.0750)	20,950
2SF1130-A31	47.1	(.0730)	29,762[a]
1SF1132-C24	48.3	(.0749)	11,770
-D4	48.1	(.0745)	8,140
2SF1132-A22	46.7	(.0739)	25,849
-D8	48.3	(.0749)	22,585
1SF1133-A11	47.8	(.0741)	25,283
-B31	49.1	(.0761)	16,370

a - Coupon had ~ 1.5% Average Moisture Content

TABLE C36

FATIGUE SCATTER STUDY
TENSION-TENSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 348 MPa (36 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = 0.0$ MPa (ksi)

Average Moisture Content $\sim 1.7\%$

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-B22	49.9 (.0773)	4,516[a]
-C25	49.4 (.0766)	4,514
2SF1117-B26	50.8 (.0787)	6,277
1SF1121-C12	47.6 (.0738)	108
-C28	48.2 (.0747)	8,635
2SF1121-A10	48.0 (.0744)	5,589
-A28	48.3 (.0749)	3,865[a]
1SF1122-A4	47.4 (.0735)	4,632
-C1	46.8 (.0725)	970
2SF1122-C32	47.7 (.0739)	6,413
1SF1130-B2	47.7 (.0739)	4,990
1SF1132-D6	47.4 (.0734)	793[a]
2SF1132-C10	48.4 (.0750)	4,140[a]
1SF1133-C3	47.5 (.0737)	5,100

a - Coupon had $\sim 1.5\%$ Average Moisture Content

TABLE C37

FATIGUE SCATTER STUCY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 95 MPa (14 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = -110$ MPa $(-16.0$ ksi$)$

Average Moisture Content $\sim 1.7\%$

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A27	48.8 (.0756)	154,860
1SF1121-B32	47.2 (.0731)	231,640
2SF1121-D8	48.0 (.0744)	45,644
1SF1122-A9	46.5 (.0721)	22,535
-C23	49.0 (.0759)	148,900
2SF1122-C14	49.0 (.0760)	10,960
-D23	47.0 (.0728)	135,850
-D32	45.7 (.0709)	16,227
1SF1130-A28	48.0 (.0744)	109,910
2SF1130-B27	48.0 (.0744)	38,160
-C24	48.1 (.0746)	108,830
1SF1132-B22	47.8 (.0741)	79,303
2SF1132-C31	48.1 (.0746)	214,070
1SF1133-A29	48.5 (.0751)	244,101

TABLE C38

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 138 MPa (20 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-16.0 ksi)

Average Moisture Content ∼ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
2SF1117-B32	48.6 (.0754)	10,720
2SF1121-A12	46.7 (.0724)	10,790
-A30	48.4 (.0750)	34,699[a]
1SF1122-B21	47.9 (.0742)	24,718
-D19	47.7 (.0740)	28,660
2SF1122-A18	47.1 (.0730)	25,630
2SF1130-C8	48.0 (.0744)	4,522
-D4	48.0 (.0744)	31,000[a]
1SF1132-D17	48.3 (.0749)	28,070
-D23	47.7 (.0739)	14,840
2SF1132-B10	48.7 (.0755)	13,400
-B27	49.0 (.0760)	17,120
-C2	47.6 (.0739)	15,230
1SF1133-C29	48.4 (.0750)	23,791
-D25	47.0 (.0729)	18,660

a - Coupon had ∼ 1.5% Average Moisture Content

TABLE C39

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 179 MPa (26 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

$\sigma_{min} = -110$ MPa (-16.0 ksi)

Average Moisture Content $\sim 1.7\%$

Coupon ID	Area mm^2 ($in.^2$)	Cycles to Failure, N_f
1SF1117-A25	48.1 (.0746)	5,270
2SF1117-B14	50.1 (.0776)	11,772
1SF1121-C16	49.8 (.0772)	15,100
-C18	49.2 (.0762)	16,300
2SF1121-D5	48.6 (.0754)	22,430
1SF1122-A7	47.1 (.0730)	6,860
-C26	49.1 (.0761)	12,951[a]
2SF1122-C16	49.2 (.0763)	12,580
-D27	47.1 (.0730)	21,617[a]
1SF1130-D16	49.6 (.0769)	10,100
2SF1130-A27	47.3 (.0734)	13,600
1SF1132-D20	48.2 (.0747)	11,395
2SF1132-D7	48.4 (.0750)	27,620
-D27	46.8 (.0726)	5,350
1SF1133-A18	48.1 (.0646)	15,820
-B14	49.8 (.0772)	6,733

a - Coupon had $\sim 1.5\%$ Average Moisture Content

TABLE C40

FATIGUE SCATTER STUDY
TENSION-COMPRESSION FATIGUE RESULTS OF NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF 221 MPa (32 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

σ_{min} = -110 MPa (-16.0 ksi)

Average Moisture Content ~ 1.7%

Coupon ID	Area mm^2 (in.^{2})	Cycles to Failure, N_f
1SF1117-A18	48.7 (.0755)	3,409[a]
-C7	48.6 (.0753)	5,610
-C10	49.9 (.0773)	2,830
2SF1117-C2	49.5 (.0767)	3,660
1SF1121-C10	49.4 (.0765)	5,300
-D22	48.2 (.0747)	3,720
2SF1121-B13	48.0 (.0744)	2,010
2SF1122-A27	48.7 (.0755)	5,270
-C21	48.0 (.0744)	5,864[a]
1SF1130-D14	49.6 (.0769)	1,270
1SF1132-A24	46.6 (.0722)	955
1SF1133-A3	48.1 (.0746)	3,040
-B5	48.3 (.0749)	3,100[a]
-C17	48.5 (.0751)	2,942

a - Coupon had ~ 1.5% Average Moisture Content

FATIGUE THRESHOLD DATA

FOR

LAMINATE 1

TABLE C41

TENSION-TENSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS AT A MAXIMUM STRESS OF 33.5 ksi

Environment: Room Temperature, Laboratory Air σmin = 0 ksi, f = 10 Hz
           Air
                        MJ Material [1]

Sample ID	Area, mm^2 (in.^{2})	Cycles to Failure, N_F	Cycles to Delamination, N_{DL} (Approximate)
578-13A	53.4 (0.0827)	10^7 N.F.[a]	-
578-23A	53.4 (0.0827)	10^7 N.F.	-
580-24A	53.0 (0.0821)	10^7 N.F.	8.7×10^6
580-11B	53.6 (0.0831)	10^7 N.F.	8.4×10^6
582-4A	52.2 (0.0809)	10^7 N.F.	5.7×10^6
582-16A	53.4 (0.0827)	10^7 N.F.	6.6×10^6
582-13B	52.8 (0.0818)	10^7 N.F.	-
594-22A	52.5 (0.0815)	1,789,020	1.49×10^6
594-1B	51.4 (0.0796)	1,903,000	1.14×10^6
596-21A	52.7 (0.0817)	10^7 N.F.	-
596-14B	53.7 (0.0832)	10^7 N.F.	-
601-12A	52.7 (0.0817)	10^7 N.F	-
603-7A	52.5 (0.0814)	10^7 N.F.	-
603-9B	53.5 (0.0830)	10^7 N.F.	-
603-11B	53.7 (0.0833)	10^7 N.F.	-
604-26A	52.7 (0.0817)	5,195,610	-
606-9B	55.0 (0.0852)	10^7 N.F.	-
606-10B	54.9 (0.0851)	10^7 N.F.	-
693-12C	56.6 (0.0878)	10^7 N.F.	-
693-15B	57.6 (0.0893)	10^7 N.F.	-

a - N.F. indicates No Failure.

TABLE C 42

TENSION-COMPRESSION FATIGUE RESULTS OF UN-NOTCHED LAMINATE 1
COUPONS TESTED AT A MAXIMUM STRESS OF -110 MPa (16 ksi)

Environment: Room Temperature Laboratory Air σ_{min} = -110 MPa (16 ksi),
f = 10 Hz Air

MJ Material [1]

Sample ID	Area mm^2 ($in.^2$)	Cycles to Failure, N.F.
1NH693-3A	55.5 (0.0861)	N.F.[a]
-5A	55.9 (0.0867)	N.F.
-9A	56.6 (0.0877)	N.F.
-14A	56.6 (0.0877)	9,745,000
-18A	55.7 (0.0864)	N.F.
-22A	56.1 (0.0870)	N.F.
-25A	55.2 (0.0856)	N.F.
-30A	54.6 (0.0847)	N.F.
-4B	55.7 (0.0863)	N.F.
-19B	56.5 (0.0875)	N.F.
-22B	56.6 (0.0878)	N.F.
-27B	55.7 (0.0864)	N.F.
-30B	54.5 (0.0844)	N.F.
-3C	55.8 (0.0865)	N.F.
-7C	54.8 (0.0850)	N.F.
-10C	56.7 (0.0879)	N.F.
-15C	59.0 (0.0914)	N.F.
-18C	53.9 (0.0836)	N.F.
-24C	55.9 (0.0866)	N.F.

a - N.F. -- Indicates No Failure

APPENDIX D

RESIDUAL STRENGTH DATA

UN-NOTCHED LAMINATE 1

RESIDUAL STRENGTH DATA

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT
0 TO 40 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 100,000 cycles.

(Number of coupons static tested = 19)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, e_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf} psi x 10^6	Failure Location[a]
1SF121-A32	0.0749	4890	65.3	0.0093	7.02	C
1SF122-A28	0.0726	5330	73.4	0.0090	8.16	1E
-A32	0.0736	4350	59.1	0.0080	7.39	C
-D25	0.0724	4010	55.4	0.0088	6.30	C
2SF122-B19	0.0744	5320	71.5	-	-	1/2 E
-C18	0.0754	5260	69.8	0.0098	7.12	C
-D24	0.0744	5120	68.8	-	-	C
1SF130-A14	0.0760	4410	58.0	0.0077	7.53	1E
-A25	0.0729	Coupon failed at 69,570 cycles				
-A31	0.0741	4530	61.1	0.0086	7.10	1E
-B15	0.0761	5480	72.0	0.0087	8.38	1/2 E
-D1	0.0740	4110	69.1	0.0104	6.59	1/2 E
2SF130-B15	0.0759	4280	56.4	0.0091	6.20	C
-D31	0.0742	5140	69.3	0.0099	7.00	C
1SF132-B23	0.0740	5100	68.9	-	-	C
-D11	0.0726	3780	52.1	0.0093	5.64	C
2SF132-A19	0.0742	5270	71.0	0.0100	7.30	C
-C25	0.0752	4850	64.5	0.0094	6.86	C
-D17	0.0748	5370	71.8	0.0092	7.80	1E
1SF133-A12	0.0732	Coupon failed at 56,629 cycles				
-B17	0.0757	5090	67.2	0.0099	6.79	C
Average			65.5	0.0092	7.07	
Std. Dev.			6.5	0.0007	0.70	
Coeff. of Var.			9.9 %	7.9 %	9.5 %	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length

E = Coupon End at or near tab, i.e., 1/2 E indicated failure ~ 1/2 in. from tab.

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 100,000 cycles.

(Number of coupons static tested = 20)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10⁶	Secant Modulus at 35 ksi, E_{s35}, psi x 10⁶	Failure Location[a]
1SF1117-B10	0.0776	4165	53.2	0.0084	6.33	6.67	C
1SF1122-A27	0.0725	3600	49.7	0.0075	6.63	7.00	C
-A30	0.0729	2725	37.4	0.0058	6.65	6.60	C
-D9	0.0731	3030	41.5	0.0063	6.59	6.86	C
2SF1122-D21	0.0727	3070	42.2	0.0067	6.30	6.60	C
1SF1130-A1	0.0735	2940	40.0	0.0069	5.80	6.48	C
-B23	0.0754	1745	23.1	0.0050	4.62	-	C
-D5	0.0750	2845	37.9	0.0057	6.65	7.00	3/4 B
-D26	0.0740	3030	41.0	0.0063	6.51	6.60	C
2SF1130-A26	0.0725	1825	25.2	0.0037	6.81	-	C
-B4	0.0742	2825	38.1	0.0060	6.35	6.86	1E
-C26	0.0750	3115	41.5	0.0067	6.19	6.60	C
1SF1132-B7	0.0748	2930	39.2	0.0066	5.94	6.73	C
-C25	0.0753	3274	43.5	0.0072	6.04	6.73	C
-D13	0.0746	2920	39.1	0.0060	6.52	6.86	C
2SF1132-A24	0.0713	4795	67.2	0.0102	6.52	6.86	C
-B30	0.0753	3490	46.2	0.0075	6.16	7.00	C
-B32	0.0743	2620	35.3	0.0059	6.03	6.14	C
-C12	0.0769	Coupon failed at 87,760 cycles					
-D3	0.0753	2850	37.8	0.0057	6.63	6.86	C
1SF1133-D11	0.0734	2375	32.4	0.0048	6.75	-	1E
Average			40.6	0.0065	6.3	6.73	
Std. Dev.			9.4	0.0014	0.49	0.22	
Coeff. of Var.			23.1%	21.2%	7.8%	3.3%	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
B = Coupon end at or near tab, i.e., 3/4 B indicated failure ~ 3/4 in. from tab.

TABLE D 3

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT
0 TO 40 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 300,000 cycles.

(Number of coupons static tested = 19)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, e_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Failure Location
18F1117-B11	0.0771	Coupon failed at 127,384 cycles				
28F1121-C13	0.0743	Coupon failed at 278,040 cycles				
-C17	0.0759	4210	55.5	0.0098	5.66	C
18F1122-A20	0.0745	3600	48.3	0.0081	5.96	C
-A26	0.0715	3710	51.9	0.0102	5.09	C
-A31	0.0729	Coupon failed at 113,093 cycles				
-C4	0.0754	4060	53.8	0.0068	7.91	C
-C10	0.0749	5210	69.6	0.0099	7.03	C
28F1122-A9	0.0725	5370	74.1	0.0104	7.12	1E
-B7	0.0758	4290	56.6	0.0090	6.29	C
-C27	0.0753	4660	61.9	0.0094	6.59	C
-D26	0.0726	4480	61.7	0.0098	6.30	C
18F1130-C4	0.0762	Coupon failed at 227,630 cycles				
-D6	0.0739	3630	49.1	- b	-	C
-D30	0.0742	4070	54.9	0.0102	5.38	1E
28F1130-A19	0.0733	Coupon failed at 84,428 cycles				
-B3	0.0744	5350	71.9	0.0096	7.49	1E
-D20	0.0744	4000	53.8	0.0101	5.33	C
18F1132-B29	0.0750	4520	60.3	0.0076	7.93	1E
-D21	0.0743	5050	68.0	0.0094	7.23	C
28F1132-B1	0.0711	Coupon failed at 181,280 cycles				
-C28	0.0755	5140	68.1	0.0096	7.09	C
-D21	0.0756	4070	53.8	0.0095	5.66	C
18F1133-A2	0.0751	4090	54.5	0.0082	6.63	C
-D14	0.0759	2790	36.8	0.0066	5.61	1E
-D29	0.0737	Coupon failed at 2010 cycles				
	Average	58.1	0.0091	6.46		
	Std. Dev.	9.3	0.0012	0.90		
	Coeff. or Var.	16.0 %	12.7 %	13.9 %		

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length
1E = Coupon End at or near tab, i.e., 1/2 E indicated failure ~1/2 in. from tab.
b - Exterior delamination too severe for extensometer to grip.

TABLE D 4

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT
0 TO 40 ksi AT 180°F, 90% R.H. IN LABORATORY AIR
f = 10 Hz

Coupons fatigue tested to 300,000 cycles.
(Number of coupons static tested = 22)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sr}, psi x 10⁶	Failure Location[a]
18F1121-C5	0.0738	2290	31.0	0.0049	6.30	C
-B22	0.0769	1440	18.7	0.0042	4.45	C
29F1121-C8	0.0753	2815	37.8	0.0060	6.30	C
-D12	0.0728	Coupon failed at 82,576 cycles				
18F1122-A1	0.0706	1630	23.1	0.0046	5.02	C
-C28	0.0751	1530	20.4	0.0035	5.83	C
-D2	0.0733	1355	18.5	0.0032	5.73	C
29F1122-A14	0.0747	1230	16.5	-	-	C
-A26	0.0722	Coupon failed at 220,930 cycles				
-B29	0.0743	2290	30.8	0.0060	5.13	C
-C15	0.0756	1675	22.2	0.0036	6.17	C
-D31	0.0718	2660	37.0	0.0057	6.49	C
18F1130-A11	0.0713	1775	24.9	0.0037	6.73	C
-D18	0.0750	1670	22.3	0.0043	5.19	C
-D20	0.0761	Coupon failed at 267,878 cycles				
29F1130-A32	0.0733	1450	19.8	-	-	C
-C16	0.0745	Coupon failed at 263,830 cycles				
18F1132-A26	0.0717	2510	35.0	0.0051	6.86	C
-B2	0.0725	2690	37.1	0.0055	6.68	C
-B16	0.0737	2625	35.6	0.0060	5.94	C
-C26	0.0755	2700	35.8	0.0054	6.63	C
28F1132-B14	0.0763	1870	24.5	0.0053	4.62	C
-D20	0.0757	1535	20.3	0.0053	3.82	C
-D30	0.0744	2270	30.4	0.0051	5.96	C
-D32	0.0755	Coupon failed at 289,749 cycles				
18F1133-A29	0.0748	Coupon failed at 269,045 cycles				
-C27	0.0758	1500	19.8	0.0041	4.89	C
-D8	0.0748	1655	22.1	0.0045	4.91	C
Average			26.5	0.0045	5.68	
Std. Dev.			7.3	0.0013	0.87	
Coef. of Var.			27.4 %	27.9 %	15.4 %	

a -- C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT -16 TO 30 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 17,750 cycles equal to a probability of survival, P_s, of 0.9.

(Number of coupons static tested = 20)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}', psi x 10⁶	Failure Location[a]
1SF1117-A14	0.0771	5600	72.6	-	-	1/4 E
-B16	0.0777	5980	77.0	0.0102	7.55	C
-C23	0.0753	4850	64.4	-	-	1/2 E
2SF1117-C7	0.0755	6180	81.9	-	7.48	1E
-C15	0.0783	4960	63.3	0.0084	7.54	C
2SF1121-C31	0.0746	5760	77.2	0.0104	7.42	C
1SF1122-C17	0.0755	5760	76.3	0.0098	7.79	1/2 E
-C30	0.0734	5770	78.6	0.0098	8.02	C
2SF1122-A7	0.0743	5800	78.1	0.0094	8.31	C
-B18	0.0739	4960	67.1	0.0082	8.18	1/2 E
-D13	0.0719	5140	71.5	0.0095	7.53	1/2 E
1SF1130-A17	0.0751	5600	74.6	0.0098	7.61	C
-A27	0.0747	5990	80.2	0.0100	8.02	C
2SF1130-B20	0.0735	5820	79.2	-	-	C
-B22	0.0743	5740	72.3	0.0091	7.95	C
-D15	0.0750	5480	73.1	0.0096	7.61	1/2 E
1SF1132-B10 -B21	0.0740 0.0747	5130	Coupon failed at 16,665 cycles 68.7	-	-	E
1SF1133-B16	0.0763	5910	77.5	0.0095	8.16	C
-C6	0.0753	5400	71.7	0.0096	7.47	3/4 E
-D5	0.0746	6170	82.7	0.0102	8.19	C
Average			74.4	0.0096	7.80	
Std. Dev.			5.5	0.0006	0.3	
Coeff. of Var.			7.4 %	6.4 %	4.0 %	

[a] C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
E = Coupon End at or near tab, i.e., 1/2E indicated failure ~ 1/2 in. from tab

D7

TABLE D 6

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT
-16 TO 30 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 17,750 cycles equal to a probability of survival, P_s, of 0.9.

(Number of coupons static tested = 20)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10⁶	Secant Modulus at 35 ksi, E_{35}', psi x 10⁶	Failure Location [a]
1SF1217-B9	0.0781	3810	48.8	0.0077	6.32	6.86	C
-B23	0.0770	4235	55.0	0.0087	6.32	6.86	C
2SF1217-C21	0.0766	4345	56.7	0.0091	6.23	7.14	C
2SF1221-A11	0.0751	3360	44.7	0.0072	6.21	6.86	C
-B31	0.0737	4725	64.1	0.0095	6.68	7.45	C
1SF1222-A24	0.0731	4670	63.9	0.0104	6.14	7.00	C
-D13	0.0724	4740	65.5	0.0093	7.04	7.45	C
2SF1222-C7	0.0749	3355	44.8	0.0065	6.89	7.29	B
1SF1210-B30	0.0755	4840	64.1	0.0090	7.12	7.45	C
-C28	0.0761	4830	63.5	0.0095	6.68	7.29	C
2SF1210-C17	0.0745	3605	48.4	0.0076	6.37	7.29	C
-D32	0.0746	3780	50.7	-	-	-	C
1SF1212-A8	0.0726	3485	48.0	-	-	7.95	C
-B25	0.0748	4200	56.2	0.0090	6.24	6.67	C
-C10	0.0750	4410	58.8	0.0096	6.84	7.14	C
2SF1212-B2	0.0719	4440	61.8	0.0088	7.02	7.45	C
1SF1213-A1	0.0720	4435	61.6	0.0092	6.70	7.29	C
-A26	0.0747	3480	46.6	0.0068	6.90	7.07	C
-D10	0.0740	4655	60.2	0.0090	6.69	7.29	C
-D18	0.0745	4440	59.6	0.0092	6.51	6.94	C
Average			56.2	0.0086	6.61	7.20	
Std. Dev.			7.2	0.0010	0.32	0.30	
Coeff. of Var.			12.8 %	12.1 %	4.9 %	4.2	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;

B = Coupon end at or near tab, i.e., 1/2% indicates failure ~ 1/2 inch from tab.

D8

TABLE D 7

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT

-16 TO 30 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

Coupon fatigue tested to 63,750 cycles equal to a probability of survival, P_s, of 0.5.

(Number of coupons static tested = 19)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, e_{ult}, in/in. in 2.0 in.	Secant Modulus at Failure, E_s, psi x 10⁶	Failure Location
1SF1117-A7	0.0757	5640	74.5	0.0097	7.76	1E
-C17	0.0778	6000	77.1	-	7.30	3/4E
2SF1117-A1	0.0739	4940	66.8	0.0091	7.34	C
-A12	0.0760	4120	54.2	0.0084	7.05	3/4E
-A32	0.0770	6060	78.7	0.0102	7.71	C
1SF1121-B3	0.0748	5950	79.5	0.0116	7.60	C
-B25	0.0748	5200	69.5	0.0099	7.02	1E
2SF1121-A29	0.0755	Coupon failed at 39,520 cycles				
-C12	0.0741	3600	48.6	0.0069	7.04	1/2E
-D14	0.0750	Coupon failed at 46,200 cycles				
1SF1122-A5	0.0734	5840	70.6	0.0110	7.57	C
2SF1122-A11	0.0734	5270	71.8	0.0102	7.04	C
-A19	0.0742	5150	69.4	0.0089	7.78	C
-A22	0.0727	5670	78.0	-	-	1E
1SF1130-A30	0.0731	Coupon failed at 50,000 cycles				
2SF1130-C1	0.0771	5250	77.8	0.0104	7.48	C
1SF1132-D7	0.0738	4930	66.8	0.0096	7.77	C
-D9	0.0735	5840	70.5	0.0095	7.57	C
1SF1133-A4	0.0736	5870	79.8	0.0100	7.98	3/4E
-B6	0.0742	5210	70.2	0.0095	7.39	1/2E
-C8	0.0758	4620	60.9	0.0068	8.96	1/4E
-C11	0.0746	5660	75.9	0.0104	7.30	1E
-D31	0.0745	Coupon failed at 39,640 cycles				
	Average	71.5		0.095	7.5	
	Std. Dev.	9.0		9.0013	0.46	
	Coef. of Var.	12.5		13.7%	5.1%	

TABLE D 8

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 1 COUPONS FATIGUE TESTED AT -16 TO 30 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 63,750 cycles equal to a probability of survival, P_s, of 0.5.

(Number of coupons static tested = 19)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_f, psi x 10⁶	Secant Modulus at 35 ksi, E_{s35}', psi x 10⁶	Failure Location[a]
1SF1117-B13	0.0772	4505	58.4	0.0091	6.42	6.73	C
-B31	0.0754	4000	53.1	0.0099	5.36	6.73	C
2SF1117-B1	0.0735	3800	51.7	0.0098	5.88	6.60	C
-C28	0.0780	4065	52.1	0.0082	6.35	6.73	C
1SF1121-B21	0.0755	3805	50.4	0.0076	6.63	7.00	C
2SF1121-A7	0.0761		Coupon failed at 42,260 cycles				
-A8	0.0758	3770	49.7	0.0081	6.14	7.00	1E
2SF1122-A8	0.0734	4840	65.9	0.0102	6.46	7.14	1E
-B20	0.0751	4315	57.5	0.0095	6.05	6.86	1E
2SF1122-C1	0.0731	4110	56.2	0.0087	6.46	7.00	C
1SF1130-B29	0.0758		Coupon failed at 30,146 cycles				
-C6	0.0753	3745	49.7	0.0080	6.21	6.60	C
2SF1130-A21	0.0742	4025	54.2	0.0086	6.30	6.86	C
-B5	0.0750	4825	64.3	0.0101	6.37	7.00	C
1SF1132-B24	0.0729	3575	49.0	0.0095	5.16	5.93	C
-D8	0.0737	3955	53.7	0.0075	7.16	7.29	C
2SF1132-D1	0.0700	3345	47.8	Coupon failed at 56,770 cycles			
-D24	0.0729			0.0078	6.13	6.60	C
1SF1133-B30	0.0758	3860	49.6	0.0075	6.38	6.73	C
-C30	0.0752	3500	46.5	0.0082	5.66	7.16	C
-D12	0.0723	3725	51.5	0.0090	5.72	6.48	C
-D17	0.0746	3860	51.7	0.0081	6.38	6.73	C
Average			53.3	0.0087	6.18	6.83	
Std. Dev.			5.2	0.0009	0.47	0.32	
Coeff. of Var.			9.7 %	10.1 %	7.6 %	4.7 %	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length;
E = Coupon end at or near tab, i.e., 1/2E indicated failure ~ 1/2 in. from tab

NOTCHED LAMINATE 1

RESIDUAL STRENGTH DATA

TABLE D9

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 TO 234 MPa (0 TO 34 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

$f = 10$ Hz

Coupons fatigue tested to 34,830 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 18)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-A16	48.6	0.0754	345	50.0
1SF1121-A28	47.2	0.0731	330	47.9
2SF1121-A21	48.7	0.0755	329	47.7
-D20	48.4	0.0750	354	51.3
1SF1122-B19	47.5	0.0737	336	48.8
-C3	48.1	0.0746	364	52.8
-D5	45.7	0.0708	323	46.8
2SF1122-A32	47.5	0.0736	342	49.6
-C14	49.0	0.0760	347	50.3
1SF1130-C7	47.9	0.0743	324	47.0
-D17	49.0	0.0759	338	49.1
1SF1132-A2	46.7	0.0724	362	52.5
-B19	46.9	0.0727	338	49.1
-C11	47.3	0.0733	336	48.8
2SF1132-A7	47.5	0.0736	347	50.3
-D26	47.0	0.0729	301	43.6
1SF1133-B24	48.0	0.0744	305	44.2
-C9	48.5	0.0751	333	48.3
Average			336	48.8
Standard Deviation			17	2.4
Coefficient of Variance			5.0%	5.0%

D 12

TABLE D 10

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 TO 234 MPa (0 to 34 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

$$f = 10 \text{ Hz}$$

Coupons fatigue tested to 34,830 cycles equal to a probability of survival, P_s, of 0.9.

(Number of coupons static tested = 19)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-B20	49.9	0.0774	316	45.8
-D23	48.1	0.0746	305	44.2
1SF1121-B2	47.9	0.0742	311	45.1
-D11	46.1	0.0714	331	48.0
2SF1121-B4	48.3	0.0749	301	43.7
-D21	48.0	0.0744	306	44.4
1SF1122-B17	47.8	0.0741	367	53.2
-C8	48.1	0.0746	377	54.7
2SF1122-B2	47.5	0.0736	330	48.3
-C2	47.9	0.0742	368	53.4
1SF1130-C12	48.1	0.0746	265	38.5
-D19	48.2	0.0747	261	37.9
1SF1132-A4	47.0	0.0729	330	47.8
-B26	47.7	0.0740	324	47.0
-C22	47.9	0.0742	331	48.0
2SF1132-A8	47.1	0.0730	283	41.1
-D13	47.4	0.0735	288	41.8
1SF1133-B21	48.5	0.0752	331	48.0
-C13	48.3	0.0748	307	44.5
Average			318	46.1
Standard Deviation			32	4.6
Coefficient of Variance			10.0	10.0

TABLE D 11

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 TO 234 MPa (0 TO 34 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 159,350 cycles equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 20)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-B21	50.1	0.0776	338	49.0
-D21	48.1	0.0745	331	48.0
1SF1121-B4	47.6	0.0738	377	54.7
2SF1121-A5	48.2	0.0747	348	50.5
-B3	47.9	0.0742	370	53.6
-D23	46.6	0.0723	351	50.9
1SF1122-B28	47.4	0.0734	340	49.3
-B29	48.3	0.0749	360	52.1
2SF1122-B12	46.9	0.0727	282	40.9
-D3	47.5	0.0736	367	53.3
1SF1130-A2	48.1	0.0746	350	50.8
-C14	48.6	0.0753	355	51.5
-D24	47.5	0.0736	Coupon failed at 27,160 cycles	
2SF1130-C25	47.7	0.0740	Coupon failed at 96,300 cycles	
-D16	48.4	0.0750	314	45.5
1SF1132-A5	45.6	0.0707	325	47.2
-B32	47.8	0.0741	367	53.3
-C23	47.9	0.0743	333	48.3
2SF1132-A27	46.5	0.0720	350	50.7
-C6	47.7	0.0739	323	46.9
1SF1133-B4	48.2	0.0747	368	53.4
-C16	47.6	0.0737	328	47.6
Average			344	49.9
Standard Deviation			23	3.3
Coefficient of Variance			6.7%	6.7%

TABLE D 12

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 TO 234 MPa (0 TO 34 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 159,350 cycles equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 20)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-B7	49.5	0.0767	260	37.7
2SF1117-A22	49.6	0.0769	262	38.0
1SF1121-B8	48.4	0.0750	301	43.7
2SF1121-A6	47.5	0.0737	250	36.2
-B5	47.5	0.0736	240	34.8
-D25	46.5	0.0720	327	47.4
1SF1122-B10	48.4	0.0750	270	39.0
-C19	48.1	0.0746	291	42.2
2SF1122-A2	47.2	0.0732	314	45.6
-B24	48.3	0.0749	272	39.4
-D4	46.8	0.0726	274	39.7
1SF1130-A21	48.4	0.0750	288	41.7
-C20	47.7	0.0739	221	32.1
-D31	48.3	0.0749	Coupon failed at 105,330 cycles	
2SF1130-D12	45.3	0.0702	Coupon failed at 54,080 cycles	
1SF1132-A15	48.2	0.0747	283	41.0
-C32	48.3	0.0748	272	39.4
-D19	47.7	0.0739	310	45.0
2SF1132-C8	48.3	0.0748	296	42.9
1SF1133-A8	47.3	0.0733	276	40.1
-B11	47.6	0.0737	235	34.1
-D23	47.9	0.0742	304	44.1
Average			277	40.2
Standard Deviation			28	4.0
Coefficient of Variance			10.0%	10.0%

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TABLE D 13

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 152 MPa (-16 TO 22 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

$f = 10$ Hz

Coupons fatigue tested to 105,460 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 21)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	in.^{2}	MPa	ksi
1SF1117-C6	47.3	0.0733	330	47.9
2SF1117-D7	48.3	0.0748	Coupon failed at 7,036 cycles	
1SF1121-C17	48.7	0.0755	295	42.8
2SF1121-A15	48.6	0.0754	315	45.7
-B14	47.9	0.0743	311	45.1
-C2	48.3	0.0748	364	52.8
-D26	46.5	0.0721	308	44.7
1SF1122-B9	48.1	0.0745	314	45.5
-C24	47.5	0.0736	335	48.6
2SF1122-A3	46.6	0.0722	335	48.6
-B26	47.4	0.0734	332	48.1
-D5	46.4	0.0719	272	39.5
1SF1130-C22	47.7	0.0739	325	47.1
2SF1130-A12	45.2	0.0701	278	40.3
-A17	47.7	0.0740	Coupon failed at 3,403 cycles	
-C31	45.2	0.0701	303	43.9
-D11	45.4	0.0704	316	45.9
1SF1132-A17	47.7	0.0739	344	49.9
-B3	47.6	0.0738	342	49.6
-D2	47.4	0.0734	Coupon failed at 4,607 cycles	
2SF1132-A14	47.9	0.0743	Coupon failed at 70,770 cycles	
-C14	47.2	0.0731	353	51.2
1SF1133-A9	47.2	0.0732	311	45.1
-A21	48.3	0.0749	360	52.2
-D27	46.9	0.0727	310	45.0
Average			322	46.6
Standard Deviation			24	3.5
Coefficient of Variance			7.6%	7.6%

TABLE D 14

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 152 MPa (-16 TO 22 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 105,460 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 19)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-C9	47.7	0.0739	295	42.8
2SF1117-C25	48.5	0.0751	297	43.1
2SF1121-A16	48.1	0.0746	335	49.0
-B20	48.5	0.0751	294	42.6
-D24	45.6	0.0707	308	44.7
-D30	47.0	0.0728	Coupon failed at 88,590 cycles	
1SF1122-B5	46.8	0.0726	315	45.7
-C27	48.7	0.0755	285	41.3
1SF1130-B17	47.5	0.0737	290	42.0
-D3	48.3	0.0749	343	49.7
2SF1130-C19	47.5	0.0734	328	47.6
-C21	48.5	0.0751	257	37.3
-D10	45.7	0.0709	337	48.9
1SF1132-A21	47.3	0.0733	288	41.7
-B5	47.4	0.0735	326	47.3
2SF1132-A16	48.1	0.0746	263	38.1
-B24	47.1	0.0730	Coupon failed at 4,257 cycles	
-C15	47.5	0.0736	332	48.2
1SF1133-A10	47.7	0.0739	305	44.2
-B18	47.4	0.0734	316	45.9
-D28	46.8	0.0725	288	41.7
Average			306	44.3
Standard Deviation			25	3.6
Coefficient of Variance			8.1%	8.1%

TABLE D 15

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 152 MPa (-16 TO 22 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

$f = 10$ Hz

Coupons fatigue tested to 255,390 cycles equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 11)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-C13	48.3	0.0749	349	50.6
2SF1117-D11	46.5	0.0722	Coupon failed at 142,720 cycles	
2SF1121-A13	47.7	0.0740	Coupon failed at 244,950 cycles	
-B32	46.6	0.0722	Coupon failed at 145,220 cycles	
-C9	49.0	0.0760	325	47.1
-C23	46.7	0.0724	334	48.5
1SF1122-C31	46.5	0.0721	292	42.3
-D26	47.5	0.0736	343	49.7
2SF1122-A12	45.4	0.0704	Coupon failed at 237,230 cycles	
-A25	46.2	0.0716	308	44.7
1SF1130-B20	47.7	0.0739	330	47.9
-D4	48.6	0.0753	Coupon failed at 194,420 cycles	
2SF1130-A1	43.9	0.0681	Coupon failed at 11,840 cycles	
-A24	46.4	0.0719	310	44.9
-B1	44.6	0.0692	Coupon failed at 74,860 cycles	
1SF1132-D13	47.5	0.0736	Coupon failed at 39,400 cycles	
-D15	48.5	0.0751	Coupon failed at 155,970 cycles	
2SF1132-A2	46.3	0.0718	363	52.6
-B26	48.9	0.0750	Coupon failed at 136,070 cycles	
1SF1133-A16	48.9	0.0758	323	46.8
-A20	49.6	0.0769	338	49.0
-B4	47.5	0.0736	Coupon failed at 66,370 cycles	
Average			329	47.7
Standard Deviation			20	2.9
Coefficient of Variance			6.2%	6.2%

TABLE D 16

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 152 MPa (-16 TO 22 ksi)
AT ROOM TEMPERATURE IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 255,390 cycles equal to a probability
of survival, P_s, 0.5.

(Number of coupons static tested = 14)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-C21	48.8	0.0757	327	47.4
2SF1117-C18	49.2	0.0763	280	40.6
1SF1121-D2	47.0	0.0728	Coupon failed at 231,080 cycles	
2SF1121-A20	48.3	0.0748	297	43.1
-B26	48.5	0.0751	Coupon failed at 32,570 cycles	
-C14	48.1	0.0745	290	42.0
1SF1122-C32	45.7	0.0708	314	45.6
2SF1122-A10	47.1	0.0730	241	34.9
-A31	46.9	0.0727	305	44.2
-C3	47.1	0.0730	Coupon failed at 100,230 cycles	
1SF1130-B25	47.5	0.0737	Coupon failed at 119,320 cycles	
-D8	46.8	0.0726	237	34.4
2SF1130-A3	47.9	0.0742	Coupon failed at 224,740 cycles	
-B11	46.6	0.0723	294	42.7
-C4	46.7	0.0724	Coupon failed at 246,140 cycles	
1SF1132-B14	48.8	0.0757	235	34.1
-D5	46.9	0.0727	Coupon failed at 29,900 cycles	
-D25	46.6	0.0723	Coupon failed at 22,890 cycles	
-D27	47.2	0.0732	290	42.0
-D32	48.0	0.0744	292	42.3
2SF1132-A6	46.6	0.0722	Coupon failed at 204,000 cycles	
-B19	47.0	0.0728	285	41.4
1SF1133-A17	48.2	0.0747	Coupon failed at 55,550 cycles	
-B7	48.1	0.0746	322	46.7
Average			286	41.5
Standard Deviation			30	4.3
Coefficient of Variation			10.4	19.4

TABLE D 17

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 to 193 MPa (0 to 28 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 27,970 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 17)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-A2	49.0	0.0760	351	50.9
-C15	49.7	0.0770	329	47.7
2SF1117-B6	50.1	0.0776	288	41.8
1SF1121-B27	48.7	0.0755	306	44.4
2SF1121-A27	48.1	0.0745	316	45.8
1SF1122-B1	45.0	0.0697	307	44.5
-D10	47.1	0.0730	334	48.5
2SF1122-B23	48.1	0.0745	302	43.8
-D20	47.7	0.0740	327	47.4
1SF1130-C23	48.5	0.0751	261	37.9
2SF1130-A4	47.6	0.0738	323	46.9
-C29	48.6	0.0753	350	50.7
1SF1132-A22	47.5	0.0737	332	48.2
-D31	47.7	0.0740	339	49.1
2SF1132-B16	47.5	0.0737	310	45.0
-D5	47.9	0.0742	335	48.6
1SF1133-D24	47.6	0.0738	310	45.0
Average			319	46.3
Standard Deviation			23	3.3
Coefficient of Variance			7.1	7.1

TABLE D 18

RESIDUAL COMPRESSIVE STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 to 193 MPa (0 to 28 ksi)
AT 82.2°C (180°F), 90% R.H. in LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 27,970 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 16)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-B27	50.0	0.0775	294	42.7
2SF1117-A13	49.7	0.0771	241	34.9
-B24	49.0	0.0759	231	33.5
1SF1121-D28	47.9	0.0743	272	39.4
2SF1121-C6	46.9	0.0727	207	30.0
1SF1122-C7	48.1	0.0746	272	39.5
2SF1122-A24	46.8	0.0726	346	50.2
-C29	48.2	0.0747	287	41.6
1SF1130-A23	47.9	0.0742	210	30.4
-D25	47.1	0.0730	245	35.5
2SF1130-A30	47.5	0.0736	271	39.3
-D25	47.1	0.0730	237	34.4
1SF1132-B29	47.8	0.0741	261	37.8
2SF1132-A12	46.6	0.0722	Coupons failed at 11,962 cycles	
-D2	48.4	0.0750	276	40.0
1SF1133-A32	48.1	0.0746	260	37.7
-B28	49.1	0.0761	265	38.4
Average			261	37.8
Standard Deviation			34	4.9
Coefficient of Variance			13.0	13.0

D 21

TABLE D 19

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 TO 193 MPa (0 to 28 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

Coupons fatigue tested to 81,770 cycles equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 17)

Sample ID	Average Area		Ultimate Stress, τ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-A3	48.8	0.0757	352	51.1
-C32	48.7	0.0755	295	42.8
2SF1117-B10	49.3	0.0764	319	46.3
1SF1121-A1	45.7	0.0709	202	29.3
-A29	47.4	0.0734	337	48.9
2SF1121-B21	49.2	0.0762	344	49.9
-D11	47.5	0.0737	318	46.1
1SF1122-B11	48.0	0.0744	326	47.3
-D12	46.2	0.0716	316	45.9
2SF1122-C13	48.1	0.0745	330	47.9
1SF1130-A3	47.7	0.0740	334	48.5
-D9	47.5	0.0736	Coupon failed at 74,493 cycles	
2SF1130-A18	47.2	0.0732	278	40.3
1SF1132-C1	46.7	0.0724	339	49.2
2SF1132-A29	47.2	0.0731	356	51.6
-D6	48.1	0.0745	337	48.9
1SF1133-A27	48.0	0.0744	344	49.9
-C4	47.8	0.0741	325	47.2
Average			321	46.5
Standard Deviation			36	5.3
Coefficient of Variance			11.3	11.3

TABLE D 20

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT 0 TO 193 MPa (0 to 28 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 81,770 cycles equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 17)

Sample ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	in.^{2}	MPa	ksi
1SF1117-B29	49.2	0.0763	289	41.9
2SF1117-A15	49.3	0.0764	283	41.0
-C6	47.6	0.0738	265	38.4
1SF1121-B30	48.1	0.0745	256	37.2
-D22	48.1	0.0746	221	32.0
2SF1121-C10	49.3	0.0764	294	42.7
1SF1122-A13	46.6	0.0723	167	24.2
-C14	47.6	0.0738	298	43.2
2SF1122-B10	47.9	0.0742	304	44.1
-D7	46.6	0.0723	270	39.1
1SF1130-B11	48.5	0.0752	190	27.5
2SF1130-A6	46.7	0.0724	265	38.5
-B13	47.8	0.0741	Coupon failed at 35,377 cycles	
-C30	46.8	0.0726	250	36.2
1SF1132-A30	47.2	0.0731	223	32.4
-D14	48.3	0.0748	260	37.7
2SF1132-B25	48.1	0.0745	Coupon failed at 77,640 cycles	
-D22	49.1	0.0761	229	33.2
1SF1133-D30	47.6	0.0738	248	36.0
Average			254	36.8
Standard Deviation			38	5.5
Coefficient of Variance			5.0%	5.0%

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TABLE D 21

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 138 MPa (-16 TO 20 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 8680 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 17)

Coupon ID	Area		Ultimate Stress σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-A21	49.7	0.0770	285	41.4
-C23	49.9	0.0774	298	43.2
1SF1121-B6	47.9	0.0742	281	40.7
-D5	47.3	0.0733	294	42.6
2SF1121-B28	48.1	0.0746	307	44.5
-D19	48.1	0.0746	287	41.6
1SF1122-B25	47.5	0.0736	238	34.5
2SF1122-A1	46.1	0.0715	303	43.9
-B15	47.5	0.0736	272	39.5
-D16	47.2	0.0732	305	44.3
1SF1130-D11	45.4	0.0704	292	42.3
2SF1130-A16	48.5	0.0751	278	40.3
-D3	47.9	0.0743	283	41.0
1SF1132-D26	47.4	0.0734	297	43.1
2SF1132-C16	48.3	0.0748	233	33.8
1SF1133-A13	48.7	0.0755	232	33.7
-B3	47.7	0.0739	283	41.0
Average			281	40.7
Std. Dev.			24	3.5
Coeff. of Var.			8.6%	8.6%

TABLE D 22

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 138 MPa (-16 TO 20 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 8680 cycles equal to a probability
of survival, P_s, of 0.9.

(Number of coupons static tested = 16)

Coupon ID	Area		Ultimate Stress σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-C1	45.9	0.0712	292	42.35
2SF1117-C9	50.4	0.0781	241	34.96
1SF1121-B31	47.9	0.0742	267	38.68
2SF1121-A1	46.2	0.0716	298	43.23
-C11	48.8	0.0757	281	40.75
1SF1122-A16	48.1	0.0746	269	39.01
-D4	46.7	0.0724	299	43.30
2SF1122-C19	48.8	0.0757	288	41.74
1SF1130-D13	49.0	0.0759	232	33.66
2SF1130-C5	48.2	0.0747	230	33.33
1SF1132-A12	47.0	0.0728	269	39.01
-B15	48.6	0.0753	273	39.64
2SF1132-A32	47.9	0.0742	237	34.37
-D15	49.0	0.0759	250	36.30
1SF1133-C32	48.0	0.0744	259	37.63
-D16	48.8	0.0757	279	40.49
	Average		281	40.7
	Std. Dev.		24	3.5
	Coeff. of Var.		8.6%	8.6%

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TABLE D 23

RESIDUAL TENSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPONS
FATIGUE TESTED AT -110 TO 138 MPa (-16 TO 20 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 19,340 cycles equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 12)

Coupon ID	Area		Ultimate Stress σ_{ult}	
	mm^2	in.^{2}	MPa	ksi
1SF1117-A10	48.3	0.0748	288	41.7
-B24	49.3	0.0764	Coupon failed at 5000 cycles	
-C4	48.1	0.0745	314	45.5
-C30	49.3	0.0764	Coupon failed at 6192 cycles	
2SF1117-A17	49.7	0.0771	Coupon failed at 12,750 cycles	
1SF1121-B9	48.4	0.0750	308	44.7
-C2	48.8	0.0757	Coupon failed at 18,162 cycles	
1SF1122-A21	47.5	0.0737	293	42.5
2SF1122-A21	48.4	0.0750	294	42.7
-D17	47.4	0.0735	Coupon failed at 7224 cycles	
1SF1130-A18	48.4	0.0750	281	40.8
-B26	48.8	0.0756	305	44.3
-D21	49.4	0.0765	Coupon failed at 5980 cycles	
-D28	47.9	0.0742	288	41.4
2SF1130-A8	46.6	0.0723	Coupon failed at 7789 cycles	
1SF1132-B17	46.6	0.0723	279	40.4
-B31	48.6	0.0754	Coupon failed at 14,300 cycles	
2SF1132-A3	47.8	0.0741	304	44.1
-C21	48.8	0.0756	289	41.9
-D29	47.5	0.0736	Coupon failed at 557 cycles	
1SF1133-B13	49.1	0.0761	Coupon failed at 14,598 cycles	
-D22	49.1	0.0761	285	41.4
Average			294.0	42.6
Std. Def.			11.2	1.6
Coeff. of Var.			3.8 %	3.8 %

TABLE D 24

RESIDUAL COMPRESSION STRENGTH
TEST RESULTS OF NOTCHED LAMINATE 1 COUPON
FATIGUE TESTED AT -110 to 138 MPa (-16 to 20 ksi)
AT 82.2°C (180°F), 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 19,340 cycles, equal to a probability
of survival, P_s, of 0.5.

(Number of coupons static tested = 11)

Coupon ID	Average Area		Ultimate Stress, σ_{ult}	
	mm^2	$in.^2$	MPa	ksi
1SF1117-A23	49.4	0.0765	Coupon failed at 1427 cycles	
2SF1117-B31	49.4	0.0766	223	32.4
-C17	50.5	0.0783	Coupon failed at 8781 cycles	
1SF1121-C3	48.3	0.0748	284	41.2
2SF1121-A14	48.4	0.0750	Coupon failed at 10,400 cycles	
-B30	47.4	0.0734	Coupon failed at 18,670 cycles	
1SF1122-B31	46.8	0.0726	Coupon failed at 11,490 cycles	
-D7	47.3	0.0733	246	35.7
2SF1122-B8	48.8	0.0757	266	38.6
-C22	47.6	0.0738	Coupon failed at 8,865 cycles	
1SF1130-C15	49.2	0.0763	264	38.3
2SF1130-A22	47.9	0.0743	Coupon failed at 18,620 cycles	
-A29	47.3	0.0733	221	32.0
-C27	48.8	0.0757	232	33.6
-D24	47.9	0.0743	Coupon failed at 14,210 cycles	
1SF1132-A13	48.2	0.0747	Coupon failed at 7,430 cycles	
-A19	48.7	0.0755	Coupon failed at 12,750 cycles	
-D30	47.9	0.0742	236	34.2
2SF1132-B22	47.5	0.0736	267	38.7
1SF1133-A19	48.5	0.0752	256	37.2
-A30	47.9	0.0743	268	38.9
Average			251	36.4
Standard Deviation			21	3.0
Coefficient of Variance			8.3%	8.3%

UN-NOTCHED LAMINATE 2

RESIDUAL STRENGTH DATA

TABLE D 25

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT 0 TO 100 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 250,000 cycles.
(Number of coupons static tested = 23)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in/in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Failure Location [a]
23FL133-A5	0.1031	13350	129.5	0.0088	14.7	1/4E
-A28	0.1055	17550	166.4	0.0124	13.4	1/4E
-A31	0.1064	17300	162.6	0.0125	13.0	E
-B9	0.1094	18150	165.9	0.0107	15.5	E
-B23	0.1047	15000	143.3	0.0104	13.8	1/4E
-C9	0.1079	17150	158.9	0.0104	15.3	E
-C22	0.1079	17100	158.5	0.014	14.0	C
-D19	0.1059	15500	146.4	-	-	E
19FL137-A26	0.1079	17850	165.4	0.0106	15.6	E
-B22	0.1135	16800	148.0	0.0093	15.9	C
-B29	0.1106	17550	158.7	0.0108	14.7	C
-C10	0.1140	17900	157.0	0.0102	15.4	3/4E
-D9	0.1106	18050	163.2	0.0105	15.5	C
23FL137-A4	0.1113	17800	159.9	0.0101	15.8	E
-C1	0.1065	16450	154.5	0.0094	16.4	E
-C23	0.1097	12650	115.3	0.0074	15.6	E
-D26	0.1088	16100	147.9	0.0088	16.8	E
18FL149-A19	0.1094	16750	153.1	0.102	15.0	E
-D32	0.1121	17500	156.1	0.0094	16.6	E
25FL149-A30	0.1074	14450	137.1	0.0104	13.2	E
-B24	0.1060	16650	157.1	0.0104	15.1	E
-B30	0.1063	17200	161.8	0.0105	15.4	E
-C28	0.1128	17100	151.6	-	-	1/4E
Average			153.0	0.0102	15.1	
Std. Dev.			12.4	0.0012	1.1	
Coef. of Var.			8.1 %	11.3 %	7.1 %	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.
    E = Coupon End at or near tab, i.e., 1/2 E indicated failures ~ 1/2 in. from tab.

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TABLE D 26

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT
0 TO 100 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 250,000 cycles.
(Number of coupons static tested = 22)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, e_{ult}, in/in in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Secant Modulus at 70 ksi, E_{s70}, psi x 10^6	Failure Location[a]
2S7133-A17	0.1069	11080	103.7	0.0086	12.1	12.4	C
-A27	0.1057	12000	113.5	0.0093	12.2	13.3	C
-b6	0.1033	9800	94.9	0.0092	11.6	12.3	E
-B7	0.1071	11820	110.4	0.0091	12.1	13.1	E
-D19	0.1047	9940	94.9	0.0101	9.4	13.3	C
-C10	0.1078	10720	99.4	0.0094	11.8	12.8	E
-D6	0.0997	11040	110.7	0.0087	12.7	13.0	E
1S7137-A7	0.1082	12850	118.8	0.098	12.1	13.6	C
-B10	0.1116	12340	110.6	0.0094	13.2	14.6	E
-C27	0.1127	10940	96.2	0.0072	13.4	14.4	E
2S7137-A6	0.10/6	9900	92.0	0.0072	12.8	13.0	C
-C16	0.1104	11540	104.5	0.0084	12.4	13.7	E
-D10	0.1087	13020	119.8	0.0086	13.5	14.6	E
1S7149-A4	0.1114	12320	110.6	0.0090	12.3	13.7	E
-B11	0.1091	11940	110.5	0.0090	12.3	13.0	E
-C11	0.1100	14460	131.5	0.0102	12.9	13.7	E
-C17	0.1103	13020	118.0	0.0096	12.3	13.1	E
2S7149-A4	0.1117	11640	104.2	0.0081	12.9	14.1	E
-B8	0.1130	13000	115.0	0.0087	13.2	13.0	3/AE
-C3	0.1121	10640	94.9	0.0072	13.2	13.7	E
-C6	0.1072	10040	93.7	0.0078	12.0	13.0	E
-C29	0.1096	12300	112.2	0.0090	12.4	14.1	C
Average			107.3	0.0087	12.4	13.4	
Std. Dev.			10.4	0.0009	0.9	0.7	
Coef. of Var.			9.7 %	9.90%	6.90%	4.80%	

a   C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.

E = Coupon End at or near tab, i.e., 1/2E indicated failure ~ 1/2 in. from tab.

TABLE D 27

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT
0 TO 100 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 10^6 cycles.
(Number of coupons static tested = 16)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Failure Location [a]
2SF1133-A15	0.1101	16750	152.1	-[b]	-	E
-B28	0.1097	16700	152.2	0.0100	15.2	C
-C14	0.1080	17400	161.1	0.0096	16.8	E
1SF1137-B15	0.1144	17600	153.8	-[b]	-	1/2E
-B24	0.1098	Coupon failed at 794,360 cycles				
-C22	0.1109	16300	147.0	0.0094	15.6	C
-D4	0.1149	14750	128.4	-[b]	-	E
2SF1137-A15	0.1121	14250	127.1	-[b]	-	E
-B3	0.1125	15200	135.1	0.0082	16.5	E
-B30	0.1076	Coupon failed at 168,000 cycles				
-D4	0.1096	12300	112.2	-[b]	-	E
-D9	0.1094	16500	150.8	-[b]	-	E
1SF1149-B6	0.1058	13350	126.2	-[b]	-	E
-B10	0.1119	16350	146.1	-[b]	-	C
-C10	0.1124	14750	131.2	0.0080	16.4	E
2SF1149-B31	0.1190	15500	130.3	-[b]	-	1/2E
-C8	0.1124	16250	144.6	0.0090	16.1	E
-C18	0.1062	14350	135.1	-[b]	-	C
Average			139.6	0.0090	16.1	
Std Dev.			13.3	0.0008	0.6	
Coef. of Var			9.5 %	8.8%	3.7%	

[a]   C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length
    E = Coupon End at or near tab, i.e., 1/2 E indicated failure ~ 1/2 in. from tab.

[b]   Exterior delamination too severe for extensometer to grip.

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TABLE D 28

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED

AT 0 TO 100 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

$f = 10$ Hz

Coupons fatigue tested to 10^6 cycles.
(Number of coupons static tested = 16)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, e_{ult}, in./in. in 2.0 in.	Secant Modulus at failure, E_s', psi x 10^6	Secant Modulus at 70 ksi, E_{70}', psi x 10^6	Failure Location[a]
2STL133-A23	0.1057	6580	62.3	0.0053	11.9	—	E
-B4	0.1066	9280	87.1	0.0059	14.8	16.0	E
-C24	0.1209	Coupon failed at 103,702 cycles					
-D23	0.1029	10340	100.5	0.0094	12.0	12.3	E
1STL137-A10	0.1118	8140	72.8	0.0057	12.8	13.1	E
-C23	0.1104	10920	98.9	0.0094	11.8	13.0	E
-D25	0.1093	10400	95.2	0.0075	12.7	13.7	E
2STL137-A5	0.1106	11340	102.5	0.0094	12.2	12.8	1/2E
-C2	0.1110	9520	85.8	0.0059	12.4	13.0	E
-C11	0.1122	9100	81.1	0.0059	11.8	12.1	E
-D19	0.1112	11100	99.8	0.0081	12.3	12.6	E
1STL149-A16	0.1125	8560	76.1	0.0059	13.0	13.5	E
-C9	0.1057	9040	84.7	0.0087	9.7	10.1	1/2E
-C17	0.1093	9420	87.0	0.0056	13.2	13.7	E
-D27	0.1095	7800	71.2	0.0053	13.3	14.1	E
2STL149-B4	0.1107	11320	102.3	0.0086	12.0	13.2	E
-D21	0.1128	10940	97.0	0.0075	12.9	13.7	E
Average			87.8	0.0071	12.4	13.1	
Std. Dev.			12.5	0.0012	1.1	1.2	
Coef. of Var.			14.2%	17.3%	8.5%	9.5%	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.
E = Coupon End at or near tab, i.e., 1/2E indicated failure ~ 1/2 in. from tab.

TABLE D 29

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT

-30 TO 80 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 250,000 cycles.

(Number of coupons static tested – 21)

Coupon ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in/in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Failure Location a
2SF1133-A24	0.0991	12300	124.1	0.0070	17.7	E
-B5	0.1043	14700	140.9	0.0098	14.4	C
-B15	0.1085	14250	131.3	-	-	E
-B27	0.1099	16790	152.7	0.0086	17.8	E
-B29	0.1073	15700	146.3	-	-	E
-C12	0.1062	14500	136.5	0.0098	13.9	1/2E
-D17	0.1055	16500	156.3	0.0090	17.4	E
1SF1137-A23	0.1116	18300	163.9	0.0095	17.3	E
-B14	0.1113	18900	169.8	0.0100	17.0	E
-C8	0.1113	17650	158.5	0.0085	18.6	E
-D13	0.1098	18000	163.9	0.0098	16.7	C
2SF1137-B5	0.1099	17400	158.3	0.0097	18.2	E
-C3	0.1120	16400	146.4	0.0090	16.3	E
-C32	0.1104	17250	156.2	0.0080	19.5	E
-D18	0.1081	16150	149.3	0.0100	14.9	C
1SF1149-A23	0.1092	17850	163.4	0.0086	19.0	1/2E
-C7	0.1075	16375	152.3	0.0100	15.2	1/4E
-D4	0.1115	17925	160.7	0.0086	18.7	E
2SF1149-A21	0.1110	15800	142.3	-	-	E
-B17	0.1065	17750	166.7	0.0092	18.1	C
-D23	0.1110	18000	162.2	0.0074	14.2	3/4E
Average			152.5	0.0092	16.9	
Std. Dev.			12.2	0.001	1.8	
Coef. of Var.			8.0	10.6	10.3	

a – C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.

E = Coupon End at or near tab, i.e., 1/2 E indicated failure ~ 1/2 in. from tab.

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TABLE D 30

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT -30 TO 80 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 250,000 cycles.
(Number of coupons static tested = 20)

Coupon ID	Average Area, in.²	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ε_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Secant Modulus at 70 ksi, E_{s70}, psi x 10^6	Failure Location[a]
2SF1133-A14	0.1078	10840	100.6	0.0086	11.7	12.7	E
-A26	0.1094	7600	69.5	0.0067	12.2	-	E
-B16	0.1069	8800	82.3	0.0066	12.5	12.7	C
-C1	0.1003	7240	72.2	0.0051	14.2	14.6	E
-C16	0.1068	12880	120.6	0.0114	10.6	12.3	C
-D3	0.1082	Coupon failed at 169,000 cycles					
1SF1137-A12	0.1061	8940	84.3	0.0071	11.9	12.5	E
-B4	0.1113	11780	105.8	-	-	13.2	E
-B31	0.1097	10720	97.7	0.0086	11.4	12.7	E
-C18	0.074	8900	82.9	0.0068	12.2	13.0	E
2SF1137-A11	0.1082	11300	104.4	-	-	12.7	E
-B6	0.1090	10180	93.4	0.0087	10.7	11.9	E
-B20	0.1117	8240	73.8	0.0060	12.3	12.6	E
-B26	0.1120	11140	99.5	0.0081	12.3	12.6	E
-C19	0.1099	11190	108.4	-	-	13.0	E
-D7	0.1090	8340	76.5	0.0060	12.8	13.2	E
1SF1149-A5	0.1052	10950	103.2	-	-	14.3	C
-B18	0.1061	9960	93.9	0.0078	12.0	12.6	E
-D7	0.1074	12440	115.8	0.0104	11.1	12.7	E
2SF1149-A7	0.1076	12600	117.1	-	-	13.7	E
-D10	0.1094	11540	105.5	0.0087	12.1	13.0	E
Average			95.4	0.0077	12.0	13.0	
Std. Dev.			15.3	0.0018	0.9	0.7	
Coef. of Var.			16.3%	22.9%	7.4%	5.0%	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length
    E = Coupon End at or near tab, i.e., 1/2X indicated failure ~ 1/2 in. from tab

TABLE D 31

RESIDUAL TENSILE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT -30 TO 80 ksi AT 180°F, 90% R.H. IN LABORATORY AIR

$f = 10Hz$

Coupons fatigue tested to 10^6 cycles.
(Number of coupons static tested = 7)

Coupon ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in/in in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Failure Location a
2SF1133-D24	0.1005	12200	121.4	0.0086	14.1	E
2SF1137-B21	0.1129	12650	112.0	-	-	E
-D8	0.1099	16600	151.0	0.0097	15.5	E
1SF1149-A15	0.1125	17650	156.9	0.0083 -b	18.9	E
-B12	0.1076	14200	132.0	-	-	E
-D22	0.1126	18350	163.0	0.0086	19.0	E
2SF1149-A32	0.1131	Coupon failed at 238,045 cycles				
-D27	0.1098	11600	105.6	-b	-	E
Average			134.6	0.0088	16.9	
Std. Dev.			22.8	0.0006	2.5	
Coef. of Var.			16.9%	7.0%	14.6%	

a C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.
   E = Coupon End at or near tab, i.e., 1/2 E indicated failure ~ 1/2 in. from tab.

b Exterior delamination too severe for extensometer to grip.

TABLE D 32

RESIDUAL COMPRESSIVE STRENGTH TEST RESULTS OF UN-NOTCHED LAMINATE 2 COUPONS FATIGUE TESTED AT -30 TO 80 ksi AT 180°F R.H. IN LABORATORY AIR

f = 10 Hz

Coupons fatigue tested to 10^6 cycles

(Number of coupons static tested = 7)

Coupon ID	Average Area, in.^{2}	Ultimate Load, P_{ult}, lbs	Ultimate Stress, σ_{ult}, ksi	Ultimate Strain, ϵ_{ult}, in./in. in 2.0 in.	Secant Modulus at Failure, E_{sf}, psi x 10^6	Secant Modulus at 70 ksi, E_{s70}, psi x 10^6	Failure Location
2SF1133-D22	0.1081	10500	97.1	0.0087	11.2	13.7	E
1CF1137-B27	0.1139	9800	86.0	0.0072	11.9	13.0	1/2E
2SF1137-C25	0.1122	9240	81.5	0.0072	11.3	12.0	E
1SF1149-A17	0.1127	9580	85.0	0.0071	12.0	13.3	E
-C25	0.1051	10840	103.1	0.0081	13.7	14.6	E
-D20	0.1120	10080	90.0	0.0069	13.0	13.7	E
-D30	0.1080	Coupon failed at 12,800 cycles					
2SF1149-B28	0.1129	12000	106.3	0.0086	12.4	13.7	3/4E
Average			92.7	0.0077	12.2	13.4	
Std Dev.			9.7	0.0008	0.9	0.8	
Coef. of Var			10.3 %	9.9%	7.4%	6.0%	

a - C = Coupon Center, defined to be middle 3.5 in. of 5.5 in. gage length.

B = Coupon End at or near tab, i.e., 1/2E indicated failure ~ 1/2 in. from tab.

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